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PART 2

SECURITY INFORMATION

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MECHANISM OF RAIN EROSION

Part 2. A Critical Review of Erosion by Water Drop Impact

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25 JUL 1966

OLIVE G. ENGEL
NATIONAL BUREAU OF STANDARDS

AUGUST 1953

WRIGHT AIR DEVELOPMENT CENTER

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WADC TECHNICAL REPORT 53-192
PART 2

SECURITY INFORMATION

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MECHANISM OF RAIN EROSION

Part 2. A Critical Review of Erosion by Water Drop Impact

Olive G. Engel

National Bureau of Standards

August 1953

Materials Laboratory
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FOREWORD

This report was prepared by the National Bureau of Standards, under Delivery Order No. 33(616)-53-9. The delivery order was initiated under Research and Development Order No. 614-12, "Structural Plastics MX 1925", and was administered under the direction of the Materials Laboratory, Directorate of Research, Wright Air Development Center, with Lt. G. P. Peterson acting as project engineer.

ABSTRACT

A critical review of the literature on the subject of erosion by water drop impact which includes some recent work done in this laboratory has been made. The types of experimental apparatus generally used by the investigators, and the factors which they found determine the extent of the erosion damage, are briefly discussed. Results of microscope and X-ray studies are presented. Theoretical estimates of the impact pressure, the results of piezoelectric pressure measurements, and theories which have been advanced as to the mechanism of the erosion process are reviewed. Questions which are still unanswered, or in regard to which further research should be done, are pointed out.

The views and conclusions of the investigators are in many cases presented in their own words. A large number of the quotations are translations.

The security classification of the title of this report is UNCLASSIFIED.

PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDER:

M. E. Sorte

M. E. SORTE
Colonel, USAF
Chief, Materials Laboratory
Directorate of Research

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1. INTRODUCTION

The problem of the erosion of surfaces by water impact has taken on a new importance in the last few years because of the severe damage produced on the leading edge and on the radar housings of high speed aircraft as a result of travel through rain. It is necessary to understand the mechanism of this type of failure (a) to be able to select structural materials, on the basis of their known characteristic properties, which will resist this type of attack, or (b) to be able to specify both the kind and the required thickness of coating material which will adequately protect the very vulnerable surface of the aluminum alloys currently used in aircraft construction.

Before new work is started on the mechanism of the erosion process it is essential to know what has already been done and what theoretical physicists and engineers have already concluded in regard to the mechanism of the attack on the basis of previous experimental work. A large part of the early research on this problem was carried out in Switzerland and Germany. It was motivated by the erosion of the low pressure blades of steam turbines by the water droplets contained in wet steam. Since this work extends back over a period of about twenty-five years, and since the results of many of the studies were published in foreign journals, it appears that an English review which would outline the experimental arrangements that were used and the conclusions that were drawn from the test results would be of considerable value to those who are currently engaged in rain erosion research.

I. TYPES OF EXPERIMENTAL APPARATUS EMPLOYED

It has been found that the same general type of erosion which follows the same steps in initiation and progress can be produced (a) by actual water drop impact, (b) by shock waves transmitted to the test specimen by a liquid, or (c) by the collapse of bubbles. A brief outline of the most used experimental arrangements follows.

1. Water Drop Impact

Grossman[1][a] refers to the water impact type of apparatus as a "simulated" cavitation condition since the impact or pressure waves are produced by a "hydraulic hammer" instead of by collapsing bubbles.

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[a] Superscript numbers refer to the list of references at the end of this report.

Wheel and Jet Apparatus

This apparatus was early used by Honegger[2] who published results of a study of water drop erosion on a considerable number of metals and alloys in 1927. The metals to be tested were made into cylindrical or prismatic rods one end of which was threaded in each case so that they could be turned into the rim of a wheel which was driven at various speeds by an electric motor. See Figure 1. A fine jet of water was maintained parallel to the wheel shaft. The test specimens were rotated through the water jet at various peripheral velocities up to 225 m/sec (503 mi/hr). With this arrangement the water drops which caused the erosion were very short water cylinders struck from the side, i.e., along a curved water surface. The test specimens were spaced around the rim of the wheel so that each was struck by the unbroken water jet. In order to vary the drop size, Honegger divided the jet of water into jets of smaller diameter.

The same general type of apparatus with minor modifications was used by deHaller[3], Mousson[4], Gardner[5], and Hengstenberg[6]. The two last named investigators studied erosion effects at peripheral velocities of 335 m/sec (749 mi/hr) and 366 m/sec (819 mi/hr), respectively. Soderberg[7] has also discussed the use of the wheel and jet apparatus in this country in the testing of materials for turbine blades. Brandenberger and deHaller[8] later used specimens in the form of a small plate in place of the round plug-shaped specimens. Von Schwarz and Mantel[9] employed a similar arrangement but instead of using a wheel carrying specimens at its periphery, they used a rotor with a test specimen at each end. Their specimens also were plates fastened to the rotor rather than cylindrical or prismatic rods. Hence their apparatus was intermediate between the wheel and jet and the rotating arm currently employed in rain erosion studies at the Cornell Aeronautical Laboratory, and elsewhere. Vater[10] later showed a picture of the rotor variation of the wheel and jet apparatus in which a series of specimens arranged along the side of the rotor was whirled simultaneously through a corresponding series of similarly spaced water jets. This arrangement allowed a given material to be tested at a number of different velocities at the same time. Vater[11] apparently also used this type of apparatus in his earlier fatigue study.

Rotating Arm Apparatus

Recently Wahl[12] and Beal and Wahl[13] have employed a propeller rotating in a horizontal plane in artificial rain. A test specimen, shaped to fit around the leading edge on top and bottom to 30% of the blade chord, is mounted at each end of the propeller three inches from the tip. The specimen velocity can be brought to 311 m/sec (700 mi/hr). Specimens of other shapes can also be mounted by means of special adapters. The use of simulated rain allows the water drops causing the damage to be of a spherical shape as is true in practice rather than a water cylinder struck from the side. Gardner[5] had actually used discrete water drops of a kind in his later work. He employed two "White" oil-fuel burner jets which discharged the water in the form of a spinning cone of finely divided particles. In the work of Wahl and Beal and Wahl, two nozzles which produced median droplets of 1.9 and 2.5 mm diameter were used to provide simulated 1-inch and 3-inch per hour rainfalls, respectively. They were mounted so that the water drops fell close to 27 feet before they were struck by the rotating specimens.

Interrupted Jet Apparatus

Frey, Walker, and Keller[14] describe an interrupted jet type rain erosion tester used at North American Aviation, Inc. The machine consists of a continuous flow high pressure pump that forces a continuous jet of water at velocities up to 268 m/sec (600 mi/hr) through a nozzle having a diameter of 0.020 inch. A slotted rotating stainless steel disk chops the jet into discrete slugs of water. In this apparatus the water drop is therefore a water cylinder struck from the end. In spark photographs the drops appear cigar-shaped. The mass of a water slug varies as the jet velocity and the width of the slots in the chopper disk. It varies inversely with the velocity of the chopper disk. For a given jet velocity and slot width the chopper velocity is varied to produce water slugs of the desired mass.

2. **Shock Wave Apparatus**

Ackeret[15] first described in 1936 a shock wave apparatus for eroding specimens. See Figure 2. A piston B, on which blows are struck with an air pressure hammer, moves in a thick-walled steel cylinder, A. The piston diameter is 12 mm. The cylinder is conical in shape at the end where the test specimen is supported by screw D. The cylinder diameter at the location of the test specimen is 6 mm. Strong shock waves are produced by means of the hammer blows and are transmitted to the test specimen by the liquid in the conical chamber. The intensity of the impact is approximately doubled due to the conicity of the chamber since in a conical tube the intensity of the pressure wave is in first approximation inversely proportional to the tube diameter.

Improvements in the shock wave device and results of further studies employing it are given in later articles by Ackeret and deHaller[16] and by deHaller[17]. In place of the air hammer, a hammer compressed by a spring is suddenly set free by means of a simple trip gear. It strikes against the piston which transmits the blow to the liquid. See Figure 3. The impact velocity is determined by the tension of the spring. It may either be calculated from the elasticity and mass of the spring, or determined directly with a cathode-ray oscillograph.

3. <u>The Vibratory Method</u> (Magnetostriction Oscillator)

The vibratory method as represented by the magnetostriction oscillator produces cavitation erosion. Cavitation is produced on the rarefaction stroke when the pressure drops below the vapor pressure of the operating liquid, and bubble collapse occurs on the compression stroke. The scope of cavitation literature is so extensive that no attempt will be made to discuss it per se. The interested reader is referred to the recent review of cavitation by Eisenberg[18] which cites 101 references. It is important to note, however, that the relative rating of materials against cavitation erosion is the same as their rating against water drop impact although the two processes may be different at least with respect to their temperature dependence as will be pointed out later. Detailed studies of the resistance of materials to erosion using the magnetostriction oscillator have been made by Gaines[19], Kerr[20], Beeching[21,22], Poulter[23], Schumb, Peters, and Milligan[24], and by Wahl[25]. The use of the vibratory method is discussed by deHaller[17] and later by Petracchi[26] who points out that test specimens mounted on tuning forks can also give good results, the main requirement being a sufficiently high vibration velocity. The tuning fork apparatus which he used had a vibration velocity of 5 m/sec (11 mi/hr) at 800 cps.

In this laboratory erosion of cold rolled steel has also recently been accomplished by use of a Crystalab Ultrasonorator. See Figure 4. This device consists of a crystal set into vibration in an oil bath. The specimen to be studied is supported in water in a beaker the bottom of which is just maintained in contact with the surface of the oil containing the vibrating crystal. Pressure waves transmitted through the glass of the beaker produce cavitation in the water which contains the test specimen.

II. FACTORS DETERMINING THE EXTENT OF EROSION

The factors which determine the extent of the erosion damage have been extensively investigated.

1. Temperature

The effect of the temperature of the liquid on the rate of erosion was investigated by Mousson[4] in 1937 both for the case of water drop impact using the wheel and jet apparatus and for the case of cavitation in which the zone of cavitation was produced by means of a double weir arrangement. In his water drop impact study the peripheral speed was 244 m/sec (546 mi/hr), the jet diameter was 3/32 inch, and the water jet velocity was 18 m/sec (40 mi/hr). He states, "A series of runs carried out with specimens of identical material with the water temperature varying from 2 to 93°C indicated that the amount of pitting is in no way dependent upon the water temperature". In his studies of the temperature dependence of erosion due to cavitation, however, he found that the erosion increased as the temperature increased. The temperature variation, however, was only over the seasonal range. It appeared, for all practical purposes, to be directly proportional to the vapor pressure. This result led Mousson to the conclusion that water impact and cavitation are fundamentally different.

Schumb, Peters, and Milligan[24] using the magnetostriction oscillator (cavitation erosion) found a maximum weight loss at 40 to 50°C in water and in 20% sodium chloride solution. They found no maximum in methyl alcohol over the temperature range studied, but in carbon tetrachloride a maximum was found around 25 to 30°C and a minimum around 18°C.

Brandenberger and deHaller[8] using the wheel and jet apparatus found no difference in the erosion attack for soft steel specimens between 14 and 55°C.

Wahl[12] and Beal and Wahl[13] investigated the temperature range between 4 and 30°C on the rotating arm tester in a 1-inch per hour artificial rain at a specimen velocity of 134 m/sec (300 mi/hr). They also found no great difference in the rate of erosion.

Vater[10], on the other hand, using water drop impact on cast 13% chromium steel found that, "At high impact speeds such as 74 m/sec (167 mi/hr), a considerably lower number of water impacts is required to produce a weight loss of one gram at 60°C (than at 10-12°C)". He found that the effect was even more marked in the case of cast chromium-molybdenum steel. This disagreement with the results of Mousson, Brandenberger and deHaller, and those of Wahl, and Beal and Wahl indicates that the question of the temperature dependence of erosion by water drop impact should be reopened. The preliminary conclusion that erosion by water drop impact is not temperature dependent should be verified or rejected. The importance of settling the question lies in knowing whether cavitation erosion and erosion by water drop impact are actually different in this respect.

2. <u>Time</u>

Honegger[2] made plots of loss in weight of the specimens against the number of impacts. As a function of time he found that in most cases the specific erosion first increases with the number of impacts and later decreases. To explain this behavior he says that as long as the surface of the specimen is strictly smooth, it is not easily attacked by the impinging water drops, and this delays the onset of erosion. As soon as the surface becomes roughened, erosion increases rapidly becuase the water impinges with explosive force on the rough spots. After the roughness has reached some depth, a layer of water remains spread over the whole surface, and this water layer acts to dampen further water blows.

DeHaller[3] also made plots of loss in weight of the specimen against total number of impacts. The curves for different metals showed no characteristic difference. A certain number of impacts was necessary to cause a decided loss in weight. This loss increased first slowly and then faster[17]. The curves had relatively uniform slopes which varied only with the materials and their characteristic properties. He does not mention the final diminution of the erosion loss discussed by Honegger. In regard to the first appearance of the onset of erosion deHaller says, "For some time the surface remains smooth and bright, followed by slight roughening; then fine cracks appear and from this moment on erosion increases rapidly. The strongest attack is at the bottom of the eroded parts; holes develop in all directions until finally a whole piece of the material breaks off. These pieces broken off are by no means microscopically small but often of the order of magnitude of a cubic mm and larger. Onset of erosion varies even for specimens cut from the same material caused by unavoidable differences in surface finishing".

VonSchwarz and Mantel[9] found that after exposing a brass specimen to their water drop impact device for 30 sec, the surface was already covered over with microscopic deformation spots the average area of which was 0.004 mm^2. They included pictures showing the progress of erosion of a brass specimen. Weight loss curves for a series of metals and alloys which they tested showed that after 25 minutes of test only simple surface deformation had taken place. They state that the erosion sets in only after the first true surface injury appears, and that the progress is similar for all materials which are to some extent deformable.

VonSchwarz[27] later made a study of the erosion of noble metals. Starting with a polished specimen of gold-platinum alloy he found that after 15 minutes' exposure to drop impact at a peripheral velocity 72 m/sec (160 mi/hr) the polished surface showed a structure in which the hard, lighter-appearing, platinum-rich mixed crystals protruded above the darker mixed crystals which contained more gold. After 30 minutes' test the platinum-rich crystals were sculptured out and there was a decided loss in weight. After 60 minutes' exposure the surface appeared roughened even to the unaided eye.

Using the rotating arm apparatus, Beal and Wahl[13], who worked mainly with plastic specimens, described the course of the erosion with time by stating that the erosion occurs first as fine pits (of the order of 0.01 to 0.02 inch across) and that the surface becomes increasingly covered with such pits as time of erosion increases until the surface is finally covered with overlapping pits.

3. Drop Velocity

Vater[11], in summarizing the factors on which the extent of erosion damage depends, lists the velocity of the emerging water jet in the case of the wheel and jet apparatus. As the water jet speed is increased, the erosion is increased. The speed of the water jet is identical with the speed of a water drop moving perpendicular to the path of an impacting surface.

Brandenberger and deHaller[8] using the wheel and jet apparatus made a study with soft steel specimens in which the water jet velocity was varied between 5 and 20 m/sec (45 mi/hr). They remark that the great dependence of the erosion on the water jet speed is striking. As a result of their study they state that comparable results can only be obtained if the water jet velocity and the impact velocity are held constant. The effect of the latter will be discussed later.

No similar study has yet been made using the rotating arm tester or the interrupted jet type tester. All of the reported results for the rotating arm tester are for the terminal (vertical) velocity of the artificial rain drops in air.

It would seem that further studies to clarify this point would be of value in a theoretical attack on the erosion mechanism. See Part V for a discussion of the bearing of jet velocity on the impact pressure.

4. Specimen Velocity

Honegger[2], using the wheel and jet apparatus, found a definite increase in erosion with increase in the impact velocity, i.e., with increase in the peripheral speed at which the specimen was rotated through the water jet. Under the experimental conditions which he used he found no erosion after 215,000 impacts when the impact velocity was 125 m/sec (280 mi/hr). There was definite erosion at speeds of 150 m/sec (336 mi/hr) and 175 m/sec (391 mi/hr), but rapid erosion occurred only at higher speeds. Although Honegger did not find a general numerical relation between the velocity and the erosion for the various metals and alloys that he tested, he did find that the specific weight loss by erosion of a specimen could be expressed as

$$c(v-125)^2$$

where c is a constant and v is the velocity in m/sec.

That 125 m/sec (280 mi/hr) is not the lower limit at which erosion occurs and that this lower limit is a function of drop size was later shown by deHaller[3]. His experimental arrangement was basically identical with that of Honegger, but the jet of water through which the specimens were rotated had a diameter of 8 mm and could be increased to 15 mm. His first experiments were of a qualitative nature to prove that erosion can occur at fairly low speeds if the water drop is sufficiently large. He found that rapid attack results for a jet diameter of 8 mm, a water pressure for the jet of 2 m (water column), and a peripheral speed of 90 m/sec (201 mi/hr). After two million impacts under these conditions his specimens of Siemens-Martin steel had craters several mm deep. He both verified Honegger's result that the erosion intensity increases with the impact velocity and contributed the additional information that the minimum velocity necessary to cause erosion is a function of drop size (i.e. water jet diameter) and number of impacts.

Hengstenberg[6] plotted specimen weight loss against velocity. His curves show a sharp upward trend at velocities above 305 m/sec (682 mi/hr). This is an important indication for predicting what the extent of damage due to erosion may become at Mach numbers greater than one. Hengstenberg found that the least resistant of the specimens which he tested was completely cut through by the jet during the course of a test at a velocity of 366 m/sec (819 mi/hr).

The increase in erosion intensity with increase of specimen velocity is also referred to by Vater[11] and by Brandenberger and deHaller[8]. It was found also by Wahl[12] using the rotating arm tester. His results indicated that the rate of erosion is a function of the velocity and rain drop size. Beal and Wahl[13] further found that "the time of exposure required to produce a given amount of erosion is inversely proportional to some high power, about the eighth, of the velocity".

5. Drop Shape

Brandenberger and deHaller[8] using the wheel and jet apparatus and soft steel specimens varied the shape of the drop by using a flattened or oval-shaped water jet. They ran tests in which the specimen struck the flattened side of this jet, and other tests in which the specimen struck the more acutely rounded side of the jet. The result was that the erosion was much more severe when the specimen struck the flattened side of the jet. They concluded from this observation that the size of the stressed surface plays an important role. They state that this fact can perhaps be compared with observations on Pelton turbines and say, "As is known, with the high pressure water turbines with the same specific speed and the same head, small turbines are much less beset with erosion than the larger units".

6. Specimen Shape

DeHaller[3], using the wheel and jet apparatus, found that the contour of the surface of the specimen that is rotated through the water jet is of great importance. He tested simultaneously specimens with circular, square, and oblong cross-sections and found that every one reacted differently. He concluded that, in general, the resistance of the specimens is greater the smaller the surface that is hit by the water jet. He says that this fact is in agreement with Honegger's statement in regard to the diameter of the jet (See Part II, Section 7) since a change in jet diameter is identical with a change in the surface area struck. He adds that no satisfactory explanation has been found for this phenomenon but that there is probably some relation between the pressures that are developed

and the size of the surface that is struck, and that it is also possible that the duration of the applied stress, which is related to the area struck, has a considerable effect. DeHaller found that the conditions most conducive to erosion were when the surface struck by the jet was concave, and when it had small holes in it. Protrusions from the surface were less endangered. Small areas 2 mm in diameter and protruding about 2 mm above the surface were found to be very resistant to erosion -- almost as resistant as a flat surface.

Vater[11] and Brandenberger and deHaller[8] also cite the specimen shape as being a factor in the intensity of the erosion damage. Beal and Wahl[13] have tested specimens with different radii of curvature from the airfoil shape to the planar. Pictures of their specimens after test show that the more acutely curved the specimen was, the greater the damage it sustained. The planar specimen suffered the least damage. However, Brandenberger and deHaller[8] state, "As is known, a plane surface is attacked faster than an arched surface;"... This difference in observations indicates that more work is needed to clarify the point. Intuitively one feels that the flat surface should be more vulnerable. The difference in observation may arise in that the light-weight water drops are deflected from the flat surface by the air in the rotating arm apparatus, whereas in the wheel and jet apparatus the water jet is operating under pressure and is much less easily deflected from its path. If this is true, the rotating arm tester is not giving a correct indication of the extent of damage on a flat surface because the drops are actually not impinging.

7. <u>Drop Size</u>

The importance of drop size was early noticed by Honegger[2] who used the wheel and jet type apparatus. He varied the drop size by dividing the 1.5 mm diameter jet initially used into nine jets having a diameter of 0.5 mm. The nine jets were arranged so that an equal area of the specimen was struck by the water and the volume of the water passed through the nine jets per unit time was also made the same as that passing through the single jet previously used. He found that smaller water drops cause less erosion damage. The amount of decrease in the erosion on decreasing the drop size was also a function of velocity. The ratio of decrease was about 1 to 5 for high speeds and about 1 to 10 for low speeds. In this connection he made a calculation of the average pressure produced between the solid surface and the drop on impact (See Part IV, Section 2) and found that the average pressure was independent of the size of the drops. To explain his experimental observation that the larger drops do cause more rapid erosion damage he states that the faster erosion from the larger drops must be due to the larger pressure surface and possibly to a varying pressure distribution over the impacted area which was not considered in the assumptions which he made for his calculation of the pressure.

Reference has already been made to deHaller's observation that the minimum specimen velocity required to cause erosion was a function of the drop size. Large drops can cause erosion at considerably smaller velocities than those required for small drops. Reference to the effect of drop size on erosion is also made by Vater[10,11] and by Brandenberger and deHaller[8]. Wahl[12] and Beal and Wahl[13] found that the rate of erosion is a function of the velocity and the rain drop size. Wahl[12] stated, "However, there is no apparent mathematical correlation between these variables".

Beal and Wahl[13] ran tests with a 3-inch per hour rainfall where the average drop size is 2.5 mm diameter, and with a 1-inch per hour rainfall where the average drop size is 1.9 mm diameter. They found that the erosion occurred three to four times faster in the heavier rainfall. However, when the drop size for the 3-inch per hour rainfall was held at 1.9 mm diameter, the erosion proceeded less rapidly. They state that, "the test results indicate that a heavy rainfall is not proportionally more severe in action than a light rainfall if the drop size is the same in each".

Frey and Walker[28] give a graph of failure time against average water slug diameter from data obtained with the interrupted jet type apparatus. Their curves appear to indicate a minimum for each material tested and an increase in failure time both for smaller and larger slug diameters.

8. Specimen Size

Reference has already been made to deHaller's[3] observation that small protrusions having a diameter of 2 mm and extending about 2 mm above the surface are not particularly liable to suffer erosion. This is in line with the observation that the smaller the area is, which is involved in the impact, the less susceptible it is to erosion. Brandenberger and deHaller[8] called attention to the fact that the size of the stressed surface plays an important role.

Frey, Walker, and Keller[14] find that the difference in the erosion resistance rating of materials by the rotating arm and by the interrupted jet type testers is a function of the area of the specimen involved due to weak spots on the surface.

Beal and Wahl[13] made a study of the effect of the angle of attack on the intensity of the erosion damage. They found that the more acute the angle was at which the water drop struck the specimen, the less intense was the erosion damage.

9. Drop Material

The effect of the drop material has been observed in studies made both with the wheel and jet apparatus and with the vibratory apparatus. Poulter[23] using a magnetostriction oscillator apparatus and grey cast iron specimens made erosion tests in alcohol, water, ether, glycerin, and paraffin oil. He found that the damage caused by water was much greater than that caused by alcohol or ether. Glycerin and paraffin oil were found to produce but little damage. He regarded the results as evidence for his hypothesis that the liquid is driven into the pores of the impacted surface by the pressure of the impact and that the damage is caused by the escape of the liquid when the pressure is suddenly released (See Part V, Section 4).

Beeching[21,22] refers to the fact that erosion can be produced in non-corrosive media such as alcohol, paraffin oil, and mineral oil in his defense of the view that the erosion attack is mechanical (See Part V, Section 2).

Vater[11] lists the kind of operating fluid as one of the factors determining the intensity of erosion damage. In a later study Vater[10] used oil instead of water as the liquid in the drop impact apparatus. He found that the impact of oil drops is less destructive than the impact of water drops. He states, "It is not known whether the molecular structure of the liquid plays any role". He also ran tests with sea water in the drop impact apparatus. With regard to this he says, "It is known that the fatigue strength in drop impact is lower for certain materials (for a definite service life) with sea water, except in the case of stainless steels, where the resistance to sea water is somewhat better and in some types of bronze and special brass where there is only a negligible difference between fresh and sea water. Differences only become evident in long-time tests. In short-time tests the mechanical stress is so high that the chemical effect of the liquid is either insufficient or not evident".

Frey, Walker, and Keller[14] refer to the fact that the water slugs from the interrupted jet type rain erosion tester consist of an oil-water mixture and conjecture that this may have a bearing on the fact that the results with this apparatus differ from those obtained on the rotating arm device. Frey and Walker[29] later report that when tap water alone was used the test results were changed for some materials. The resistance of Plexiglas (methyl methacrylate plastic) was reduced to half, the resistance of Neoprene was increased by about 20%, but the resistance of glass fabric polyester plastic laminate was not significantly changed. The improvement in the case of Neoprene appears to be related to the fact that the oil-water mixture previously used as an eroding fluid swelled the Neoprene.

10. Specimen Material

The erosion intensity varies widely with the specimen material, and the principal objective of the early studies was to rate materials with respect to their ability to withstand the attack of water drop impact. Honegger[2] already singled out tensile strength as an important property of a water drop erosion resistant material. In general, tensile strength parallels Brinell hardness. He found, however, that there was a great difference in the behavior toward water drop attack of three varieties of cast iron which had equal Brinell numbers but were produced by different methods. He concluded from this that correlation between erosion resistance and hardness only exists when metals of similar structure are considered.

DeHaller[3, 17] found that, in general, resistance to water drop erosion is a function of the mechanical properties of the materials such as yield strength, Brinell hardness, and resilience, and is independent of their resistance to corrosion. Certain special bronzes having a very high chromium and nickel content were found, however, to be much more resistant to erosion than could be expected from their mechanical properties. They were about as resistant as high class tungsten and molybdenum steels although their tensile strength was only 70-80 kg/mm^2 (99,600-114,000 psi) as compared to 120 kg/mm^2 (171,000 psi) for the latter. DeHaller came to the conclusion that increasing the surface hardness of these metals by some kind of treatment would give even better results.

Hengstenberg[6] found that, in general, the harder materials offer the greatest resistance to erosion. He states that there are exceptions to this rule, however, especially in the case of erosion by the spray which forms when the specimen passes through the jet.

Qualifying the water impact stress as one of short, unusually hard blows of low energy content on a microscopically small area, vonSchwarz and Mantel[9] divided materials in general into two groups with respect to this type of damage. The first group embraced materials in which the work of elastic deformation is lower than the impact energy given to the metal by a single blow. If the material is not plastically deformable, as is the case with glass, the spots struck are shattered. In most cases a rather extensive deformability is present and the surface material at the spot struck is deformed until the excess impact energy is used up. In this way cold working appears at this spot so that the next chance blow which hits it will meet up with a higher resistance to deformation until after thousands of single blows the limit of ability to deform is reached and the surface is broken. They found that the following properties gave greatest water drop impact resistance to metals in this group:

(1) great hardness

(2) great ability to deform while cold

(3) extensive cold working properties

They state that the high capacity for cold working of certain alloys gives them high water impact resistance in spite of an inferior Brinell hardness, and maintain that this explains why Brinell hardness was not a consistently good criterion of water impact resistance.

In the second group they placed all materials whose elastic work of deformation is so large that the energy of a single water blow is not sufficient to deform them. In their test of materials of Brinell hardness over 300 kg/mm^2 no noteworthy deformations were observed. In this case the damage generally set in first at imperfections of the texture. Often after several hours test entire grain clusters were thrown out of the stressed surface by the water. This appeared to them to be a case of endurance resistance of grains which had an accidentally unfavorable orientation for the stress and in which the intergranular connections played an important role. For materials of the second group they found that the resistance against water drop impact is determined by:

(1) hardness

(2) the endurance strength of their grain structure joints.

Since all materials are more or less beset with imperfections and grain structure inequalities, it is hard to determine the separate effect of these two qualities. VonSchwarz and Mantel predict that by observing the guiding principles outlined it should be possible to develop water impact resistant copper alloys in which hardness and single crystal endurance strength could be brought to a high value by precipitation hardening.

Brandenberger and deHaller[8] made a study of the effect of the notched bar impact strength of a material with respect to its water drop erosion resistance. The material was boiler plate. In the as-received condition it had a notched bar impact strength of 4.9 mkg/cm^2. After being artificially aged, the notched bar impact strength was reduced to 1.1 mkg/cm^2. No changes of the static strength properties were introduced by the aging, however. The result of the study was that the notched bar impact strength had apparently no effect on the erosion resistance of the steels investigated.

Vater[11] investigating the relatively low velocity range of about 150 mi/hr found that certain low alloy steels of high tensile strength had a fairly low resistance against water drop impact erosion. He ascribed this to their greater susceptibility to oxidation and their correspondingly low resistance to the chemical attack of fresh water. On the other hand, the steels which have greater resistance to the chemical attack of fresh water had a greater endurance strength against water blows.

Beal and Wahl[13] tested mainly plastic materials although some metals were also studied. They made a study of the relative rain erosion resistance of glass and quartz. Glass and quartz tubes having a radius close to that of the standard test specimens were filled with cast resin and mounted on special adapters for testing. They found that the quartz had considerably less rain erosion resistance than the glass although it was harder and more abrasion resistant. They concluded that, "No correlation of resistance to erosion with general physical properties has yet been obtained. Soft, relatively resilient, non-brittle coatings of Neoprene or polyethylene have rain erosion resistance comparable to aluminum and alloy steels which are hard and brittle. Yet glass which is about equivalent in hardness but more brittle than normal steels has many times the erosion resistance of steel". Their good results with glass are quite different, however, from the results obtained by deHaller[3]. The explanation is probably to be found in the hardness of the glass which they used. Apparently only a very hard glass is rain erosion resistant.

In order to develop a file-hard plastic surface, Beal and Wahl milled 325 mesh Colmonoy crystals of chromium carbide together with 320 mesh aluminum into a polyester resin. The results indicated that the high hardness produced in this way does not greatly increase the ability of the material to resist erosion.

They also made a study of the effect of the bond strength between plies of cloth in a plastic laminate on its rain erosion resistance. Preliminary tests showed that this factor did not have an appreciable influence on the initiation of erosion. But laminates with good bond strength had greater resistance to erosion after it had started than laminates with poor bond strength.

Beal and Wahl also investigated the effect of using foamed or honeycomb type of core in glass laminate "sandwich" construction. The results of this study indicated that with thin face materials a foamed core tends to increase the rain erosion resistance of the "sandwich". They ascribed this to the fact that the honeycomb core does not offer as continuous a support to the laminated face as does the foam type of core.

11. Blemishes

DeHaller[3] found that small holes in a specimen favored repid erosion. Ackeret[15] states, "It is indeed known that excavations favor impact corrosion and that the velocity of erosion increases very rapidly after the building of the first small hole". Frey[30] states, "It has also been observed that flaws in the surface of a material hasten its failure considerably, with the erosion originating at the flaws and progressing from there into the surrounding material".

Vater[11] made a study on cast carbon steel, cast martensitic steel, and cast austenitic steel. The first series of specimens were so chosen that no blemishes were perceptible to the eye. Under the microscope at one hundred-fold magnification inclusions showed up which are commonly to be expected in any cast steel. A second series of specimens out of the same material were so chosen that they contained small blemishes. These ranged in depth from about 1 mm up and occupied a range of area of from 1 to 2 mm^2. Other specimens were supplied with artificial blemishes to about the same extent by means of a 1 mm drill. The specimens were weighed on an analytical balance at the beginning of the study. Their weight was again determined after 3, 6, 9, 12, and 15 hours of drop impact stress at a velocity of 68 m/sec (152 mi/hr). The result was that the specimens containing pores in general showed larger loss of weight for the same amount of water impact stress than did the pore-free specimens. Vater pointed out that natural depressions generally occasion a greater weight loss than synthetic ones, and ascribed this to the important grain differences which are often present with the natural pores.

Beal and Wahl[13] studied the effect of blemishes in the form of artificial pits and slots both in solid plastic specimens and in coatings. The solid specimens were methyl methacrylate plastic and a glass fabric polyester laminate. A brittle and a rubbery coating were used. The holes, about 0.040 inch in diameter and 0.025 or 0.030 inch in depth, were in some cases drilled and in other cases molded into the specimen. The slot blemishes were 0.030 inch wide and 0.020 inch deep. In regard to their results they state, "The study of the influence of surface defects showed that neither the time of initiation of erosion nor the rate of erosion were affected to any great extent by surface defects in the case of methyl methacrylate or glass laminates. In the case of coatings, surface defects do not materially influence the initiation of erosion but the continuation of erosion in areas where defects occur is considerably more rapid than in surrounding areas".

The difference in the results obtained by Vater and those obtained by Beal and Wahl is interesting. Even in the case of artificial blemishes Vater found that the erosion was increased. The difference may spring partly from the fact that Vater was investigating metals and Beal and Wahl were investigating non-crystalline plastic materials. It could also be attributed to the way in which the extent of erosion damage was estimated in the two studies, or to the size of the artificial blemishes. If the blemishes are too large, the raindrop will see them as separate surfaces. Only the very small blemishes will act as pressure multiplying centers. It may be rewarding to make further studies of this kind in which the blemishes are introduced under a microscope.

Beal and Wahl[13] in their discussion on laminates, on the other hand, report that, "Small pinholes or other surface irregularities have a decided effect on the initiation of rain erosion. Therefore, for greatest rain erosion resistance the smoothest surface practicable is required."

Beal and Wahl found that plastic laminates which are free of air bubbles or dry spots (void free laminates) have slightly greater resistance to rain erosion than laminates resulting from the average production process in which such blemishes might be expected to be found. This was also found to be the case by Frey and Walker[31] using the interrupted jet type apparatus.

12. Protective Finishes and Coatings

Honegger[2] investigated the possibility of protecting one metal with another. In regard to results on electrolytically chromed steel he states, "Obviously, the advantage of this operation lies in the fact that the beginning of the erosion may be postponed, but as soon as the surface of the metal has been roughened, erosion takes place almost as rapidly as with non-treated metal."

VonSchwarz states, "It is a known fact that specimens with roughened surfaces are more easily attacked than those with smooth surfaces." In a study using specimens of gold-platinum alloy he found after 30 minutes of drop impact stress at a velocity of 72 m/sec (160 mi/hr) that the weight loss of a specimen, the surface of which was etched with aqua regia prior to test, was 5 mg whereas the weight loss for a specimen having a polished surface was only 0.8 mg. After a very long exposure to water drop impact stress the

weight losses of the two samples were about the same because during the course of the test the polished surface had become roughened and holes had formed. VonSchwarz also made a test with pure platinum specimens one of which had a polished surface and the other a roughened surface. After 15 minutes the weight losses for the polished and for the roughened specimen were 1.9 mg and 4.9 mg, respectively.

To determine what effect surface conditions may have on the speed of erosion, deHaller[3] tested five specimens of cast steel with different surface finishing. The conclusion he drew from this study was that polishing retards the onset of erosion but has no effect on the speed of progressing. Later, deHaller[17] stated, "An inoxidizable protective layer, glazing, chromium plating, nickel plating, etc., is without effect".

Poulter[23] found that filling the pores of the surface to be tested with a film-forming material produced a marked decrease in the extent of erosion damage. He also used paraffin oil as a protective coat on the surface but found it to be much less effective in preventing erosion than the film-forming material.

Vater[11] and Brandenberger and deHaller[8] both cite surface condition as a factor in the intensity of erosion damage.

Wahl[12] and Beal and Wahl[13] made extensive tests of the protection afforded by plastic and rubber coatings. Graphs of their data for various thicknesses of a given coating material indicate that the effectiveness of a coating increases as its thickness increases. Of the coating materials which they have tested, the synthetic rubber, Neoprene, appears to be the most satisfactory. All three electrical grades of Neoprene coatings which they tested had fair to good erosion resistance for one to two hours when used in a film thickness of 10 mils. Of the three electrical grades of Neoprene coatings they found the 3 M-Neoprene system to have the best resistance to erosion. They state that this may be due to the fact that the 3 M-Neoprene coating is a modified compound or is copolymerized with other materials which has the effect of retarding the crystallization of Neoprene.

Shapiro[32] determined the tensile strength and elongation at rupture of ten top coats whose rain erosion resistance had been evaluated on the rotating arm tester. From his results there appears to be a direct linear relation between per cent elongation of a film and its rain erosion resistance. Although results of tensile strength measurements did not indicate that this property was critical, he concluded that a top coat having both high tensile strength and high elongation properties was most desirable for use as a leading edge coating. Preliminary results on the effect of the film thickness on the results of tensile strength and elongation measurements indicated that the film thickness introduced no significant difference.

III. THE MICROSCOPIC PROCESS

The gross factors which determine the intensity of the erosion damage were discussed in Part II. This part is concerned with an examination of the progress of erosion from a microscopic standpoint.

1. Results of Microscopic Studies

The study of vonSchwarz and Mantel[9] was the first investigation of this type. They used mainly polished specimens of easily etched materials and followed the course of the erosion with the metal microscope and the analytical balance. The water blow stress was supplied by the rotor and jet apparatus (See Part I.). After 30 seconds' testing time at a velocity of 72 m/sec (160 mi/hr) on a brass specimen they found that the entire stressed surface was covered with microscopic "boiled-up" spots (elevations and depressions) the average area of which was 0.004 mm^2. They show a picture of the deformation spots at 500-fold magnification. On account of the shortness of the test time they assumed that these deformations were the result of one or of several impacts. Their observation led them to conclude that the water impact does not work equally over the entire stressed surface but rather that individual pressure peaks of extraordinary magnitude build up on isolated spots since, in order to produce damage spots, the pressure must exceed the strength which the free surface is able to bear without becoming deformed. In order that a deformation should take place on the brass specimen referred to, they calculated that the pressure exerted by the water impact must be at least 9000 atm. Furthermore, since the deformation took place very quickly, they assumed that the effective pressure peaks were considerably higher. On the other hand, they concluded that the energy content of the individual water blow must be very moderate since even lead withstands the stress relatively long.

In regard to local pressure peaks, Vater[10] makes the following statement, "At very high speeds of impact the exposed surface shows small local deformation from which the effect of locally high pressure peaks can be assumed". He shows a surface deformation in a flat copper sheet which he says was probably caused by only one impact of an 8 mm diameter water jet. The cross-section of this hole, which he also shows, is almost perfectly conical without any indication of a lip, or metal splash at the surface. Holes in chromium-molybdenum-steel, of which he also gives a picture, show a definite metal splash around the periphery. He states, "It was found that such local pits do not occur with every impact, but that one impact will often cause several mostly smaller pits. The variation in form of these pits is practically unlimited".

Kyropoulos[33] has recently questioned the necessity of such high pressure peaks. He points out that in the case of cavitation the supporting cement about the crystal grains is eroded away. Hence it is not a question of the pressure necessary to deform a smooth polycrystalline surface (which would be of the order of magnitude required by vonSchwarz and Mantel) but rather it is a question of the pressure necessary to deform the single crystal grains which are sculptured out and exposed by the erosion of the grain cement. This pressure is only 1/4 (in the case of cubic face-centered crystals) or 1/15 (in the case of hexagonal crystals) of the pressure required to deform the smooth polycrystalline surface. Kyropoulos states that this effect "deprives the deformation argument against 'low' pressures of its physical basis unless much refined measurements can demonstrate, against present indications, that deformation takes place with the strong materials quoted with intact crystal boundaries".

Although Kyropoulos has restricted his observation in regard to the erosion of the grain cement to cavitation, vonSchwarz (See Part II, Section 2) observed a similar sculpturing out of single crystals as a result of water drop impact in the case of a gold-platinum alloy and in the case of pure platinum. Hence this argument is equally valid for maintaining that much lower pressures than those assumed by vonSchwarz and Mantel exist in this case also unless it can be demonstrated that the deformation takes place in a smooth polycrystalline area. In regard to the observations of vonSchwarz and Mantel, it is necessary to know whether the specimen on which these observations were made was very highly polished prior to the test.

Vater[11] discussed a metallographic investigation of damage to a cast austenitic steel specimen which had been exposed for 15 hours at a velocity of about 150 mi/hr to water blow stress with the wheel and jet apparatus. It showed considerable pitting wear which consisted partly of an etching and roughening of the surface, partly in a fine tear formation, and in some spots in a breaking out of the material. A cut was made through this specimen. This revealed that the water impact stress had already led to formation of glide-lines and hair-tears. Vater interpreted the damage as being due to a repeated stress (cyclic loading) of the material. The repeated stress was characterized by the special property that it works on microscopically small areas and that because of this even the smallest depression takes on importance.

A very informative study of this kind was carried out by Vater[34] on the water blow endurance of pure iron. This test material was chosen because of its homogeneous structure and great purity. The specimen material was recrystallized and the specimens were given a very high polish. Almost no blemishes and very few non-metallic inclusions could be recognized in the specimen surface under the microscope. The wheel and jet apparatus was used to supply the water stress. The jet diameter was 8 mm, water jet pressure 3 m (water column), and the specimen velocity 39 m/sec (87 mi/hr). After 1.26 million water blows, slip bands and twin formation could be detected. After 5.6 million water blows, the twin formation was considerably more important, corrosion had set in preferentially along the twin bands, and individual grain boundaries had become more strongly conspicuous. Corrosion could also be detected along the grain boundaries but was not as general here as on the twin bands. Another picture after 5.6 million water blows showed a strong local erosion. This consisted in small broken out spots which made their preferred departure from the twin bands. A lesser amount of erosion went out from the grain boundaries. After 7.7 million water blows the damage had progressed further and after 15.4 million water blows extensive damage had taken place.

The detection of slip bands and twins is evidence of the mechanical nature of the attack. Ewing and Rosenhain[35,36] were among the first to discover such lines in metals and to infer that plastic deformation or flow in metals occurs through translational slip and twinning. They say, "There are in general two modes by which plastic yielding takes place in an aggregate of crystals. One is by simple slips, where the movements of the crystalline elements are purely translatory and their orientation is preserved unchanged. The other is by twinning, when rotation occurs through an angle which is the same for each molecule in the twinned group. Both modes are often found in a single specimen of metal and even in a single crystalline grain".

The strong twin formation which was observed in the iron specimens as a result of water impact stress was interpreted by Vater as an impact effect on the basis that such deformation for iron can only rarely be induced by static loading. In this connection Tipper and Sullivan[37] say in regard to Neumann lamellae or deformation twins, "Similar bands, which may or may not be true twins, are commonly produced in α-iron, if the metal is subjected to shock, when they are not formed under static conditions of loading". Geil and Carwile[38], however, have recently obtained the deformation twins with static loading at low temperatures in iron. They obtained some twin formation at high temperatures but found that more stress is required to produce a given amount of twinning at high temperatures than would be required at low temperatures.

Kyropoulos[33] has pointed out that the appearance of hydraulic damage is characteristic of the properties of the material rather than of the process which causes it. He says, "The exceptional case of the formation of Neumann bands may be used to gain deeper insight into the damaging mechanisms".

A search was recently made in this laboratory for deformation twin formation in an alclad aluminum alloy specimen which had suffered erosion on the rotating arm tester. A cut was made through the specimen in the eroded area. It was mounted in Bakelite and polished and etched to remove all cold work due to the sectioning process. No evidence of twinning was found under magnifications up to 2000 diameters. See Figure 5. However, it appears that it has not yet been clearly demonstrated that true mechanical twins form in face-centered lattices. A study of twin formation in a body-centered material, in specimens eroded at a series of velocities, and in specimens of different size and shape may be rewarding in a search for the damage mechanism.

2. Results of X-Ray Studies

Brandenberger and deHaller[8] reported results of an X-ray reflection study of specimens of three types of Krupp soft iron of different grain size which were eroded by water drop impact using the wheel and jet apparatus. The experimental conditions were: peripheral velocity 42 m/sec (94 mi/hr), jet diameter 6 mm, and jet velocity 21 m/sec (47 mi/hr). The X-ray patterns of all of the specimens of soft iron showed identical changes under drop impact loads regardless of grain size. The X-ray patterns showed a series of changes during the course of the study. Before exposure to drop impact, the patterns consisted of spots. After exposure to an increasing number of impacts, the individual spot patterns were converted by peripheral broadening into interference rings. After this, further change did not occur in the patterns when exposure to drop impact was continued. No radial broadening of the rings was observed. The 310 ring was split into the K_α doublet even after exposure. In the case of a soft iron specimen of medium grain size, X-ray pictures taken at increasing distances from the point of maximum stress showed that the peripheral broadening decreases as the distance from the point of maximum stress increases.

They investigated also the eroded metal fragments by means of the powder method. The powder patterns were homogeneously black interference lines. Some interference points were superimposed on them. The lines showed only a small amount of radial broadening and the splitting of the K_α doublet was clearly apparent. In this respect the particles removed by drop impact stress differ from soft iron filings. The latter show strong lattice distortion.

Brandenberger made an X-ray investigation of surfaces after they were eroded by sand, cavitation, and shock waves, respectively. Patterns obtained from these specimens went through the same stages of development as those just described for a surface eroded by water drop impact. Peripheral broadening of the interference points with only minor radial broadening is apparently characteristic of X-ray patterns of the first phases of inhomogeneous plastic deformation in crystalline matter regardless of the cause of erosion. The same changes in the X-ray pattern of soft iron can be obtained by ordinary plastic deformation as a result of bending. In this case peripheral broadening is first observed and radial broadening only after extensive bending. After considerable radial broadening has taken place, the splitting of the K_α doublet disappears and the 310 interference appears as a single broad ring.

Abraded and sand blasted surfaces of soft iron have an X-ray pattern in which the doublet splitting of the 310 interference is completely absent due to extensive radial broadening. The 310 line, appearing as a single ring, is also strongly blurred. Sand blasting results in more severe deformation than sand erosion.

A comparison of X-ray patterns of static ductile fracture, static brittle fracture, fatigue fracture and dynamic fracture have yielded the following information. X-ray pictures of static ductile fracture show that as a result of this type of fracture there is strong peripheral and radial broadening of the interference points so that the 310 interference appears as a broad, blurred line without any doublet splitting. Only outside of the contracted area does the radial widening decrease and the 310 interference split somewhat into the K_α doublet. Almost identical changes in the interference pattern are observed in the case of brittle static fracture. In the case of brittle static fracture, however, the radial as well as the peripheral broadening of the interference points decreases with distance from the fracture more rapidly than in the case of ductile static fracture, i.e., a smaller area of the structure undergoes changes in crystal state. In the fracture area, however, the two static types of fracture are identical and are characterized by maximum plasticity of the crystal lattice. In the case of fatigue fracture the X-ray patterns of the fracture area show no characteristic changes of the crystal state. In close proximity to the fracture area there is only moderate broadening of the interference points. In the case of dynamic fracture there is both extensive peripheral and extensive radial broadening of the interference points but the doublet splitting of the 310 interference remains. The radial broadening falls off markedly and the peripheral broadening diminishes considerably with distance from the point of fracture. In dynamic fracture, therefore, there is marked deformation of the crystal lattice restricted to a very small region. The extent of the region affected is the main difference between the static and dynamic fracture types.

The changes in the crystal are the translational slip and twinning which occur in plastic deformation. (See Part III, Section 1). These effects increase with increased loading. Brandenberger and deHaller found that the mean linear distance between slip planes in an eroded metal surface is 10^{-4} cm (0.00004 inch). The crystal fragments removed by drop impact also have a mean linear size of 10^{-4} cm although some were 10 to 100 times larger. With the use of the factor of 200 this approaches the lower limit of the diameter of eroded holes observed by Beal and Wahl[13] (0.01 to 0.02 inch diameter).

Brandenberger and deHaller state that in the light of the X-ray analysis of static and dynamic fracture of iron and of erosion fracture of iron by water drop impact, the erosion fracture lies between the ductile static and the fatigue fracture. They state also that there are certain regions in which the erosion fracture has neither the characteristics of a static nor of fatigue fracture and imply that there is possible indication of dynamic separation. Static stresses causing a change in crystal state comparable to that found in eroded surfaces would require exceeding the elastic limit but would be insufficient to fracture the material. On the other hand, they point out that cyclic loading can cause fatigue fracture. It would result in much smaller change in the crystal state and would also require that the elastic limit should be exceeded. With consideration of the low pressures measured experimentally (See Part IV, Section 2) which are, nevertheless, apparently able to cause erosion, they conclude that one must assume that in erosion a relatively small stress causes a plastic deformation which is disproportionately large as compared with other types of deformation.

Recently an X-ray study by back reflection of an alclad aluminum alloy specimen which had suffered erosion on the rotating arm tester was made in this laboratory. A picture in the eroded region showed that the α_1 and α_2 lines of the 224 ring were broadened so that they merged to the unaided eye. A picture taken in an uneroded portion of the specimen showed these lines to be clearly distinct. Magnification of the picture taken in the eroded region shows that a vestige of separation still exists. See Figure 6. This evidence confirms the result that Brandenberger and deHaller obtained but seems to reveal a more extensive radial broadening than they found. Two factors may have a bearing on this difference. Namely, our eroded specimen was alclad aluminum alloy whereas that of Brandenberger and deHaller was soft iron. Also, the erosion of our specimen was produced at a very much higher velocity (about 400 mi/hr) than the erosion of the specimen used by Brandenberger and deHaller (94 mi/hr). This point should be investigated further. It is important because it is

a key to understanding the type of fracture which is involved in erosion by water drop impact. It would seem that the use of X-ray methods in determining the fracture type could be carried considerably further. An X-ray study of specimens eroded at various velocities should be made to determine if there is a transition in the fracture type with increase in velocity. Simultaneously, X-ray studies should be made of the fracture types in the same materials of which the specimens are made.

IV. LIQUID-SOLID IMPACT

The impact of a solid against a solid has been extensively studied, and the theory regarding it is well known. The impact of a solid against a liquid, or of a liquid against a solid presents a more complex problem because of the flow properties of the liquid. The impact of a small solid against a large body of liquid has been considered in water-entry problems related to projectiles. The impact of a small mass of liquid against a large solid, of which the impact of a water sphere against a solid surface is a special case, has not been solved.

1. The Steps in Drop Collapse

It has been conjectured that if more were known about the steps in the collapse of a liquid drop on striking a solid surface at very high speed it would prove of value in working toward a solution of the problem of erosion by water drop impact. Some information of this nature is already available. Worthington[39], employing spark photography, made a study of the forms assumed by drops of liquids when they fell vertically onto a horizontal surface. His interest in this matter was aroused by the marks made by drops of water and mercury when they fell onto a smoked glass plate. Here the lampblack was swept away in concentric circles and radial striae. The patterns varied with the height of fall of the drop. He concluded that a slight initial disturbance of symmetry is required to determine the formation of arms. It may be that irregularities in the surface allow the drop to spread with less frictional resistance in one direction than in another, and also that oscillations of the drop about its mean figure while it falls through the air have an effect. He found that the tendency to form radial arms increases with the height of fall. By increasing the size of the drop, the number of rays was also increased. He further concluded that the drop required the same time to reach its maximum spread whatever the diameter of the spread.

Worthington[40, 41, 42] also made an extended study of the impact of drops with liquid surfaces. This work is of much

interest to the problem of erosion because of the indication found by vonSchwarz and Mantel that the very first step in erosion may be the formation of "boiled-up" spots of microscopic dimensions. The splash of a viscous liquid is not far removed from the splash of a metal. Worthington remarks, in regard to the splash of metals due to impact of a projectile, that the whole kinetic energy available in an impact on armor plate would not raise the temperature of the projectile through more than a few hundred degrees Fahrenheit still less melt any great amount of it. He concludes that under the enormous pressure the physical properties of the plate material are altered so as to change the conditions of liquefaction. He states that examination of a piece of a metal splash in armor plate showed no traces of liquefaction having occurred, and he refers to the work of Ewing and Rosenhain[35, 36], on slip as an explanation of plastic flow, as being a clue to what may take place in such a metal splash. His conjecture was proved to be correct nearly fifty years later by Brandenberger and deHaller[8] in their X-ray investigation of dynamic fracture. See Part III, Section 2.

In this laboratory we[43] have recently made a study of the steps in the collapse of a drop when it strikes a solid surface. The wash out of the water was mapped chemically. To accomplish this a very small crystal fragment of sodium dichromate, held on the point of a needle, was inserted into the bottom surface of a drop just before it fell from a dropping pipet. The solution of this oxidizing agent is heavier than water and remained in the bottom of the drop. The drop was then allowed to fall onto a glass plate covered with a filter paper which was previously wet with acidified starch and potassium iodide solutions. A typical print of the wash of the drop is shown in Figure 3 of Reference (46). The water which struck first and which contained the sodium dichromate washed to the periphery of the drop. The water which struck last essentially did not flow.

To obtain some idea of the shapes assumed by the drop in the process of wash high speed moving pictures were taken of collisions of a drop with a surface. The camera was operating at approximately 10,000 frames per second. Figure 1 Reference (46) shows the collision from a fairly low height of fall, and Figure 2 Reference (46) shows the collision from a height of fall close to twenty feet. In both pictures it is observed that the top of the drop remains undeformed. It is apparent that the top of the drop does not know that the bottom has struck. In the more intense impact a circle of standing spray is observed around the periphery of the wash. This spray effect is quite spectacular in the beautiful pictures of high speed water drop collisions with the blade of the rotating arm tester taken by Wahl[44]. His pictures, however, do not reveal how the bulk of the drop behaves before it is spread out in a sheet of water.

2. Pressure Under an Impacting Water Drop

The destructive force causing water drop erosion results from the collision of the specimen with the water drop. The question of the order of magnitude of the pressure which is developed has been discussed since the very first studies were begun. Efforts have been made both to calculate the pressure from theoretical considerations and to measure it experimentally by means of a piezoelectric pressure gauge.

Theoretical Estimates of the Pressure

Honegger[2] early made a theoretical estimate of the pressure. He says, "The exact calculation of the pressure and the distribution of pressure between the surface and the drops, considering the velocity, the surface tension and viscosity of the water, involves such mathematical difficulties that it could not be carried through". The equation for the pressure p which he did obtain was

$$p = 4 \times 10^{-6} v^2$$

where the velocity v is expressed in cm/sec and p is given in kg/cm^2. To develop this equation he assumed that at the first instant of impact the center of gravity of the drop was moving at velocity v. He further assumed that after some time Δt the center of gravity was moving at velocity $v/2$ and that during this time the center of gravity had moved through a distance equal to one-fourth of the drop diameter. He then applied the impulse momentum equation,

$$m(v/2) = p\ f\ \Delta t$$

where m is the mass of the drop and f is the mean contact area between the deformed drop and the surface. The values of m, Δt, and f are:

$$m = \pi/6\ d^3 \quad \gamma/g$$

$$\Delta t = \frac{d/4}{3v/4} = d/3v$$

$$f = \pi/4\ (d/2)^2 = \frac{\pi d^2}{16}$$

so that

$$p = 4\ v^2 \quad \gamma/g$$

For a velocity of 225 m/sec (506 mi/hr), which he obtained with his water drop impact device, this equation gives the mean pressure as 2000 kg/cm^2 (28,400 psi).

For the pressure resulting from a water drop impact deHaller[3] wrote the well known equation for the collision of two flat elastic bars, that is,

$$p = \frac{V \rho_1 \alpha_1}{1 + \frac{\rho_1 \alpha_1}{\rho_2 \alpha_2}}$$

where ρ_1 = density of water; α_1, α_2 are the speed of sound in water and in the test material, respectively; ρ_2 is the density of the test specimen; and v is the relative speed. This equation does not take into account the spherical shape of the drop. Frey[30] has recently also written the equation for the elastic collision of two rods with flat ends. His equation neither takes into account the curvature of the drop nor the yield of the impacted surface.

Brandenberger and deHaller[8] as a result of their observation of the dependence of erosion on the jet velocity and jet shape question the use of the elasticity equation in a later publication. They say, "If this representation explains well the dependence of the erosion on the impact velocity, it cannot reproduce the effect of the water (jet) velocity and the size of the impact surface. For a jet released entirely in single drops one must substitute the relative velocity in the above formula, $w = (v^2 + U^2)^{1/2}$. However, the increase in w for increasing v is by far not large enough to be able to explain the increased attack on the sole basis of the increase of the relative velocity".

Vater[10] states that the impact pressures calculated from this equation are not sufficient to explain the results obtained in actual test. He observed a relatively high velocity fatigue strength for aluminum and copper alloys as compared to steels and concluded that the stress at the same impact speed is higher, the higher the value of the modulus of elasticity of the material. His objection to the elasticity equation given by Ackeret and deHaller seems to be mainly that this equation does not give enough importance to the elasticity of the material. Using Hertz's theory he calculated the ratio of the stresses caused by impact of a given ball on a surface of steel, copper, and aluminum, respectively. He found that the ratio is approximately 100: 80: 60. The ratio calculated by use of the equation for the elastic collision of two flat rods shows considerably less spread. The application of the Hertz theory in this connection, however, does not appear to be justified. The Hertz theory applies to static or to very slow collisions. Love[45], for example, says, "Hertz's theory of impact takes no account of the

dissipation of energy; the compression at the place of contact is regarded as gradually produced and as subsiding completely by reversal of the process by which it is produced. The local compression is thus regarded as a statical effect".

Recently an equation for the pressure which results when a solid surface strikes a liquid sphere was developed in this laboratory[46]. It is based on assumptions which are borne out by the observations that were made in this laboratory on the steps in the collapse and wash of a drop. See Section I. The treatment predicts that the maximum impact pressure does not exist at the center of the circle of impact in the impact plane in the case of a liquid (sphere)-solid impact, but rather it exists around a circle having radius $2 r \bar{v} / c$. Here r is the radius of the sphere, c is the speed of sound in the liquid, and $\bar{v} = 2 (1 - \alpha) v_o$ where v_o is the specimen velocity and α is a coefficient which tells what fraction of the velocity v_o is imparted to the liquid molecules on the average. The coefficient α implicitly takes into account the viscosity of the liquid. If α should ever become unity, the radius of the circle of contact would be zero and the maximum pressure would occur at the first point of contact as would be true for a rigid solid.

The diameter of the circle of contact at maximum pressure should be about the same or less than the diameter of eroded craters. When v_o is 400 miles per hour the diameter of the circle of contact at maximum pressure is 0.0036 inch. Beal and Wahl[13] found the crater diameters to be from 0.01 to 0.02 inch at a velocity of about 400 miles per hour. Consequently, the calculated diameter of the circle of contact at maximum pressure is from 0.2 to 0.4 of the observed diameter of eroded holes. This is good agreement since the pressure would not be expected to decline sharply and the circle of contact could widen considerably before the pressure fell below the breaking strength of the surface material.

The pressure equation, which takes into account the spherical shape of the drop, the yield of the specimen surface, and, implicitly, the viscosity of the liquid by means of the coefficient α , is

$$P = \frac{\alpha c \rho v_o}{2 \left(1 + \dfrac{\alpha c \rho}{2 c' \rho'}\right)}$$

where ρ, ρ' are the density of the liquid and of the solid, respectively; c, c' are the speed of sound in the liquid and in the solid, respectively. α and v_o have already been defined. The value of the coefficient α was estimated from the high speed pictures shown in Figure 8. At high velocities it approaches unity. The corrections which consideration of the viscosity of the liquid and of the spherical shape of the drop introduce both tend to reduce the value of the pressure.

For a speed of 35 m/sec (78 mi/hr) this equation predicts a pressure of 246 kg/cm^2 (3500 psi). For the same velocity the elasticity equation used by Ackeret and deHaller predicts a pressure of 485 kg/cm^2 (6900 psi). The highest experimental pressure found by deHaller for this velocity using a piezoelectric pressure gauge was 310 kg/cm^2 (4410 psi). Since deHaller's water drops were cylinders struck from the side, the pressure under them should have been approximately halfway between the pressure between a sphere and a flat surface, 246 kg/cm^2 (3500 psi), and that between two flat surfaces, 485 kg/cm^2 (6900 psi). This is seen to be the case and constitutes indirect evidence in support of the equation.

This equation is subject to any valid criticisms which can be raised against the use of the impulse momentum equation or to the use of elasticity theory in estimating theoretically the pressure produced by the impact of a solid surface and a liquid sphere.

Piezoelectric Pressure Measurements

DeHaller[3] attempted to measure the impact pressure experimentally with a piezoelectric pressure gauge having a piston diameter of 1.5 mm. In regard to possible losses in his measurements he says, "For a total capacity of cell, cable, and grid of 15 cm, an initial charge of 15 to 20 electrostatic units decreases by 50% in approximately two minutes which is sufficient to determine pressures which last only fractions of a second". Calibration was accomplished by placing weights on the piston and measuring directly the deflection of light on an oscilloscope. The pressure measuring cell was attached to the rotating wheel of his water drop impact apparatus and was rotated through the water jet at high speed. The electric charges of the rotating cell were transferred by means of slip rings and brushes on the stationary amplifier. This required long cables. He was able to limit the total capacity to 30 cm. The maximum value of pressure obtained for a peripheral velocity of 35 m/sec (78 mi/hr) was 310 kg/cm^2 (4410 psi). The elasticity equation which deHaller wrote for the pressure would have given a value of 485 kg/cm^2 (6900 psi) for this relative velocity.

The experimental measurement of the impact pressure made by deHaller has been criticized by vonSchwarz and Mantel[9], by Schroter[47], and by Beeching[21, 22]. As has already been noted vonSchwarz and Mantel obtained evidence that the area of the very first points of damage was about 0.004 mm^2. The pressure receiving surface used by deHaller was about 400 times larger than this, and on this basis vonSchwarz and Mantel maintain that the experimental piezoelectric measurement was not valid. Schroter stated similarly that blows taking place on a smaller area than the measuring probe used by deHaller could not be determined exactly. Beeching, on the basis of the evidence that plastic deformation takes place in the eroded surface, further maintained that plastic flow in the metal cap which covered the quartz crystal would itself modify the measurement. He also objected that the crystal could not be uniformly compressed throughout its length in the very short time of the duration of a single impact.

It may be remarked that even with the benefit of the progress in science and engineering of the past twenty years, it would not now be possible to make a piezoelectric gauge with a probe area less than 0.2 mm^2 which is still 50 times too large in terms of the damage area observed by vonSchwarz and Mantel. It would, of course, be possible to observe whether higher pressures were obtained as the probe area was diminished. The objection raised by Beeching is analogous to the Uncertainty Principle in that the pressure being measured permanently modifies the pressure gauge itself. Measurements made below the plastic yield point of the metal cap material, of course, would not be affected.

3. Results of Shock Wave Studies

In answer to the criticism of vonSchwarz and Mantel, Ackeret[15] replied, "One can raise the objection that it is not quite certain whether the quartz cell correctly indicated such strong blows, and that consequently the observed agreement (with calculated pressure) was only simulated. Especially, the above named authors take the view that the measuring probe used by us was much too large and yielded only a strongly reduced average value. Although a number of good reasons refute this view, we have undertaken by means of an experiment based on different principles, to find support for our view, which was arrived at over a period of time, that no pressure increase takes place in the liquid volume above the simple impact pressure, and that the initial decisive pressures for the erosion are of the moderate order. We have built a shock wave apparatus with which it is possible to corrode metal surfaces by means of sound-, or better shock-waves produced in the water". The apparatus, which is described in Part I, allowed the production of impact type pressure strain in complete absence of gases, with chemically inactive liquids, and without local pressure peaks for the reason that pressure-differences in a travelling pressure front had sufficient time and distance to become equalized, and that the production of the pressure wave by the piston was already uniform.

Erosion of the test specimens resulted on operating the apparatus for 10 to 12 hours and had the same appearance as cavitation or water drop erosion. Ackeret comments that apparently the absence of gas and of the hypothetical pressure peaks postulated by vonSchwarz and Mantel occasioned no recognizable difference. He concludes, "The present state of affairs is strange because the metal investigators insist on the high pressures which the hydrodynamic investigators cannot find".

Using an improved model of the shock wave apparatus, Ackeret and deHaller[16] found that when the apparatus was filled with crude oil an aluminum surface exposed to the shock waves was notably attacked after a total of 150,000 blows at an impact number of 10 per sec and a blow strength of 155 kg/cm^2 (2200 psi). They state, "It is characteristic that the surface first becomes simply uneven. Only after this do holes form". They then exposed a similar specimen to a non-impact type of pressure load produced with a Diesel-fuel pump and found no erosion at all for larger impact numbers and greater amplitudes. They concluded from this observation that the steepness of the wave front entering the material is very important.

In a different series of experiments they investigated the effect of liquid shocks on an amorphous substance. The liquid for this study was distilled water. The specimens were of common and of optical stress-free glass such as is used in photo-elastic measurements. The advantage in using glass was that damage below the surface could be detected. After 330,000 blows at a pressure amplitude of 173 kg/cm^2 (2460 psi) common glass contained numerous both large and small broken-out spots. The optical glass showed a superficial similar damage which had not progressed as far since it was examined after only 120,000 blows at 128 kg/cm^2 (1820 psi). However, planes of failure were visible on the inside. Some of these did not reach the upper surface. The result was of interest in that it showed that the failure could take place completely shut off from the liquid. Brandenberger and deHaller[8] also point out that the fracture below the surface indicates that the impact pressure does not reach the yield point of the material since otherwise the fracture would have appeared on the surface rather than below it. They conclude from this that an impact pressure of 400 kg/cm^2 (5690 psi) is sufficient for erosion of metals with a much greater yield point under the assumption that impact type stress with a very steep wave front takes place.

It is interesting to note in this connection that Vater[10] states, "Under repeated impacts by a liquid jet we have never observed, so far, in flawless materials erosion starting below the surface, not even below casehardened or nitrided surfaces". The explanation of this difference of opinion may possibly be found in the intensity of the impacts used. Vater worked mainly in the low velocity fatigue range which will be discussed in Part V.

V. THE EROSION PROCESS

During the twenty-five years in which erosion by water drop impact has been investigated a number of ideas have been contributed to explain both the nature of the process and its mechanism.

1. A Fatigue Range

Since erosion by water drop impact is a repeated or cyclic process, it is logical to assume that it is also a fatigue process at least in the low velocity range. Vater[11] found that the fatigue strength against fresh water blows of steel and cast steel types can be represented in dependence on the tensile strength and Brinell hardness in the same way as the results of bending fatigue or twisting fatigue under the simultaneous effect of fresh water. He plotted Wöhler-lines to ascertain the endurance limit of several structural materials against water drop impact stress. The Wöhler-lines are a plot of the reciprocal weight loss against the relative velocity. The intersection of the lines gives the velocity below which no weight loss is produced after indefinitely long duration of test. The slope of the left branch of the curve gives the rate of progress of the erosion with increasing velocity. The slope was steepest for the hardest of the materials investigated.

Beal and Wahl[13] postulated that the erosion was a fatigue or corrosion fatigue process in the low velocity range. They visualized a velocity limit, however, above which every blow produced by itself an eroded spot.

In this connection Poulter[23], using gray cast iron specimens and the vibratory apparatus, which produces erosion by cavitation, says, "Now, if the cavitation-erosion action were due primarily to a fatigue effect of the metal surface as a result of its being repeatedly stressed it would be expected that mercury would have a very large erosive effect since the forces involved would be much greater than in the cases of the other liquids, whereas, at moderate amplitudes it produces less erosion than water".

2. Chemical or Mechanical Nature

Whether or not the erosion process is chemical or mechanical in nature has been a source of considerable discussion. An acceptable picture for the process must be able to explain all of the observed facts. A strictly chemical view of the mechanism could not, for example, explain (a) the erosion of inert substances such as glass and synthetic plastics by water, nor (b) the erosion of any type of material by an inert liquid such as oil. It could also not explain (c) why the shape or size of the drop or the velocity of the impact are so important in determining the rate of erosion, (d) why a coating of a non-oxidizing metal of low mechanical strength was found to be useless, or (e) why hardness, strength, and microscopic structure are more important in determining the resistance of materials to this erosion than inability to oxidize. Finally, it could not explain (f) the translational slip and twinning which have been observed in eroded specimens, (g) the changes in X-ray patterns, or (h) how Poulter, using the vibratory method with absolute alcohol as the operating fluid, found that the eroded metal existed as finely divided metallic fragments. Poulter says in regard to his observation, "This, of course, does not prove that in the case of water, the hydrolysis does not take place on the surface of the metal but it does provide an eroded metal surface which is free from iron hydroxide".

On the other hand, the concept that this erosion is purely mechanical, i.e., that it only occurs because of the mechanical effect of the impact between the surface and the liquid drop cannot explain (a) why erosion occurs more quickly with the wheel and jet apparatus if the water for the jet is always fresh than it does if the water for the jet is recycled[8]. It can also not explain (b) why sea water is ever more effective as an eroding agent than fresh water since the density difference between them is slight, or (c) why water is better as an eroding fluid than oil[10]. The adherents of the mechanical explanation have some defense against the third objection since oil has both lower density and lower sound velocity than water as well as a greater viscosity than water all of which should tend to reduce the impact pressure.

It seems to be necessary to conceive of the process as being both mechanical and chemical. At high velocities the mechanical character becomes determinative. At low velocities chemical effects become manifest and are more important with some liquids than with others. But mechanical effects are also present at the low velocities and are probably capable of producing the erosion observed at these velocities without the concomitant chemical activity. This view is essentially in agreement with the statement of Honegger[2], "With the large velocities used, the erosion is, for the most part, of a mechanical character. In many other practical and important cases, it is exceedingly difficult to separate the mechanical erosion from the chemical corrosion which accompanies it". Some sixteen years after Honegger made this statement, Brandenberger and deHaller[8] wrote, "But it seems to be a fact that in the important problem of drop impact erosion the mechanical stresses cannot be separated from the corrosion effect".

In discussing cavitation erosion, Beeching[21] says, "When, in addition to the foregoing considerations, account is taken of the fact that even the most corrosion-resistant metals may be eroded by cavitation in non-corrosive media such as alcohol, paraffin, and mineral oil, and that inert materials such as glass may also be eroded, it becomes clear that the basis of the attack is mechanical and that pitting will occur as a result of the plastic deformation, embrittlement, and fracture of the surface layers by the stresses resulting from cavitation, even in the absence of a corrosive medium. However, the arguments presented above, leading as they do to the conclusion that cavitation erosion is essentially a mechanical attack, must not be taken to imply that where corrosion is possible it will play no part".

Vater[11] points out that for some time the erosion has been considered as predominantly a case of repeated stress and that the chemical effect has been regarded as negligible. As a result of his own studies he concluded that the presence of a chemically active liquid had an important bearing on the erosion process. According to his results there is an important simultaneous corrosion effect of the operating liquid along with the impact stress due to the mechanical effect of the liquid particles. He says, "As the results of this water impact fatigue study show, the hypothesis of the predominant mechanical effect of stress through liquid blows can no more be upheld when it is a case of fresh water, sea water, or other chemically active liquid; it can be valid if the erosion is caused by oil, for example". Vater summarizes his stand in regard to the erosion process by stating, "the damage as a result of water impact stress caused by cavitation and direct water blows takes place through the oft repeated mechanical action of the liquid drops and its simultaneous corrosion effect. The more the mechanical effect is increased, the more naturally the effect of corrosion is masked". In evaluating Vater's emphasis on the chemical aspects of the process one must recall that his experiments were carried out in the low velocity fatigue range.

In discussing the first steps in cavitation damage, Schröter[47] says, "The microscopic observation of the first traces of damage on the surfaces of materials showed that very small damage centers are built restricted to minute areas whose size often lay below the dimensions of the grain structure of the metallographic ingredients of the material. On the basis of these dimensions it is possible that the hard to observe beginnings of damage lie in the molecular region where one can hardly discern between physical and chemical processes. Yet the observations show clearly that the mechanical attack of cavitation is sufficient by itself for the purpose of damaging very resistant materials without the slightest chemical influence. Damage could be observed for example on all feasible test plates of chemically inert materials, as of synthetic resins, glass, Resistex, etc.".

Beal and Wahl[13] conclude also that it is not possible to picture the erosion process to be that of chemical attack alone. They state that, "It is possible, however, that chemical attack may occur along with the action of stress, as in the well known phenomena of stress-corrosion in metals. ... Tentatively, it seems proper to keep in mind the fact that rain erosion might be explainable as a corrosion-fatigue process as well as a fatigue process and to hope that further information on this will be uncovered".

3. Initiation Centers

Ackeret[15] points to the possibility that the erosion may start off at the weakest points in the surface. In the case of a cast iron surface he calls attention to the microscopic inclusions of graphite and states that after relatively few blows the graphite is thrown out of the surface. Since graphite has only a moderate strength it could be damaged by pressures of the order of magnitude of the water hammer equation. He says, "The erosion progress with other materials is somewhat less certainly known. But there also one can follow how the smallest imperfections in the material, which are quite unimportant with the relatively gross stress of the normal fatigue test, are attacked and picked out".

Brandenberger and deHaller[8] made observations which appear to bear out this view. In their article they include pictures which show that the structure of inclusions is reflected in the form of the eroded holes. Elongated slag yields fibrous erosion whereas spherical inclusions yield more nearly round holes.

Gardner[5] says that materials with a Brinell hardness of 600 are not completely immune from erosion at an impact speed of 1000 ft/sec (682 mi/hr). He states, "The most satisfactory explanation is afforded by the supposition that the pressure is generated not on a smooth surface, but at the bottom of a small pit in the metal. The stress distribution in this case would be completely altered and tensile stresses much greater than the pressure itself would be possible across the fibres surrounding the apex of the cavity, especially in materials with little or no ductility. It seems probable that the existence of such irregularities in the surface of the metal is essential for the erosion of these hard materials to begin".

There is a theoretical basis for thinking that microscopic pits on the surface can act as erosion nuclei. Such microscopic pits, especially if they are more or less conical in shape, will act as pressure-multiplying centers. The process was treated by Rayleigh[48] in its simplest formulation. In the case of a conical tube the amplitude of vibration of the sound wave varies inversely as the square root of the section of the tube through which it is advancing. This is the basic principle of the ear trumpet. If microscopic pits of more or less conical shape exist even in a highly polished surface, they may serve to multiply the pressure by a factor of 4 or 5 or even more. It is logical to believe that such a mechanism may be at work. The experimenters who worked with the wheel and jet apparatus rotated their specimens through the water jet at high speed. Yet the <u>first evidence of erosion was always found to be individual pits</u> rather than a welt of the diameter of the jet across the face of the specimen. The first damage sites must have been either points where the pressure multiplication took place, or else they were weak spots in the material surface. A search should be made in polished surfaces for pits which could act as pressure-multiplying centers.

4. Erosion Mechanisms

A number of ideas have been advanced to explain how the erosion may take place.

Melting

From tests of cavitation erosion, using the vibratory apparatus, Nowotny[49] reported that during the collapse of the vapor bubbles temperatures up to 2000°C may develop which might cause oxidation or melting of the surface during cavitation. VonSchwarz[27] carried out an investigation with precious metals to test the possibility of such a mechanism for erosion in the case of water drop impact. He used gold-platinum alloy consisting of mixed crystals of platinum and gold. The surface of the specimen was etched with aqua regia. After five minutes of drop

impact stress at a specimen velocity of 72 m/sec (160 mi/hr), the hard crystals of high platinum content were already seen to be protruding from the surface due to erosion of the softer crystals of high gold content. After longer periods of stress the sculpturing out of the harder crystals was more and more completely accomplished. The melting range of the gold-platinum specimens, one having a polished surface and one having an etched surface. He concluded from this study, "Since the nominal melting point of pure platinum is 1773°C it is impossible to assume that these destructions could be caused by melting or oxidation". His conclusion does not, however, appear to be completely justified if one considers the micro-mechanism of failure. His experiments in no way proved that very high temperature peaks existing over sub-microscopic regions for infinitely small periods of time did not exist.

In regard to the possibility of the local high temperature peaks of Nowotny, Brandenberger and deHaller[8] say, "While this possibility cannot be rejected entirely with cavitation, in the shock wave apparatus no such temperature peaks could appear. Besides, according to this conception materials with high melting point should be very resistant. Figure 23," in reference 8, "which represents the drop impact study with different metals of the same strength but with very different melting points shows that this is not the case". They also cite the work of vonSchwarz[27] in this connection.

Hydraulic Action

Vater[10] compares the erosion of metals by water drop impact to the erosion of rocks by water.

Beal and Wahl[13], however, as a result of a photographic study of drops impinging on the blades of the rotating arm tester, state, "Even with the great detail obtained in the pictures, no apparent hydraulic action due to water flow was observed. This fact obviates one of the theories advanced that the erosion was caused by hydraulic action much in the same manner that earth is eroded away by high pressure streams of water".

A similar conclusion can be drawn from the microscopic study of an alclad aluminum alloy specimen which was carried out in this laboratory. See Figure 5. Although the smooth rounded curves which show up in the high magnification are evidence of a water wash action, the shear pit walls indicate that water wash per se was not the prime instigator of the erosion. The water-smoothing probably took place after the pits were formed.

Liquid Penetration

Poulter[23] proposed a mechanism based on observations which he made on pieces of glass and quartz rod which were exposed to high pressures in the presence of liquids such as water, alcohol, and glycerine. When the pressure was both developed rapidly and released rapidly no fracture of the glass and quartz rods was observed. If the pressure was raised rapidly and released slowly fracture also did not occur. But if the pressure was raised, maintained for a period of time, and then rapidly released, fracture occurred. He was led by these observations to the conclusion that the liquid penetrated the solid. On a sudden release of the pressure, the escape of the entrapped liquid caused fracture. The explanation is quite plausible for the experiments which Poulter performed where the time during which the pressure was maintained was from 5 to 20 minutes. It is hard to see, however, how in the short time (microseconds) of a high speed water drop impact, much liquid could be driven into the specimen surface by the pressure which acts. Poulter defended this theory by experiments with the vibratory apparatus in which the specimen surface was coated with a film-forming substance, or with oil. He found that this treatment did reduce the amount of erosion. The amount of reduction was greater when the film-forming substance was used than when oil was used.

Electrical Effects

Petracchi[26] calls attention to the possibility of electric currents being generated by microcells formed in adjacent crystals as a result of the alternating mechanical stresses and the motion of the liquid, the specimen operating as anode and cathode. Although he directs this explanation to cavitation erosion, if such electrical charges are generated, they would also appear as a result of the alternating mechanical stresses in water drop impact. It is doubtful, however, if such a mechanism could account for the erosion of amorphous materials such as glass and synthetic organic materials such as plastics and rubbers. In this connection Brandenberger and deHaller[8] state, "It is a known fact that corrosion depends to a large degree on the state of motion of the water. Even electrolytic potentials can be determined between places of a pipe line in which the type of flow, laminar or turbulent, or only the speeds of flow are different. The latter effect is very pronounced. Differences in speed of 2 m/sec (4 mi/hr) already cause an increase of 1 mV. It is possible that in drop impact tests where much larger differences in speed occur this electrolytic effect may obtain significant importance".

Calculations made in this laboratory indicate that when the impact velocity is 600 mi/hr, the velocity of the radial water wash of the drop is 1380 mi/hr.

Crystal Orientation

Honegger[2] suggested that, "It is probable that incidental properties of the material such as orientation and arrangement of the crystals have a large influence upon the resistance to erosion".

In regard to the possibility that the erosion mechanism may involve crystal orientation, deHaller[17] says, "One has attempted also to bring the crystalline structure of the metals into play. In fact, the propagation velocity of pressure waves varies according to the orientation of the crystal; if this is different for two neighboring crystals, the pressure wave at the end of an instant will have penetrated further in one crystal than in the other; the zones compressed, and therefore deformed, find themselves in the immediate vicinity of parts not yet deformed, and the internal equilibrium necessitates the presence of tangential stresses at the surface of separation. A calculation based on the mathematical theory of elasticity shows that the stresses are of the same order of magnitude as the normal pressure and they are not able to explain the rupture. This explanation will not be of value moreover for amorphous and isotropic materials such as glass".

Chemical Action

In attempting to explain cavitation erosion in terms of chemical attack, Marboe[50] considers the tearing apart of water to expose unsaturated bonds and says, "If the ocean, the single molecule of Langmuir, is whipped by the propeller of a ship, breakage of chemical bonds, dissociation, occurs. The same is true for water fractured under high negative pressure and for cavitation occurring in an ultrasonic field or in a Reynolds tube".

Very recently, also, McCrary[51] has suggested the application of the Helmholtz double layer. He says, "Cavitation bubbles could be, by virtue of their surfaces, little vehicles impinging the metal surface, not with mere neutral water, but with concentration of H and OH ions".

It would appear that the best explanation for the charged liquid surface is the concept advanced by Hardy[52] and which is now well known in surface chemistry. Hardy said, "If the stray field of a molecule, that is of a complex of these atomic systems, be unsymmetrical, the surface layer of fluids and solids, which are close packed states of matter, must differ from the interior mass in the orientation of the axes of the fields with respect to the normal to the surface, and so form a skin on the surface of a pure substance having all the molecules oriented in the same way instead of purely in random ways. The result would be the polarization of the surface, and the surfaces of two different fluids would attract or repel one another according to the sign of their surfaces".

The vapor-liquid interface of a cavitation bubble, or the air-liquid interface of a water drop, or still the solid-liquid interface of an impacted water drop should, in the light of Hardy's concept, constitute a charged surface. Furthermore, this surface of oriented molecules could form within the time required for a molecule to recognize the fact that it was in a surface. This is considerably shorter than microseconds.

The erosion mechanism, however, cannot be explained solely in terms of this phenomenon. If this were the <u>only</u> mechanism of the erosion, a million drops falling on a specimen from a dropping pipet would produce as much erosion as a million high speed impacts. This is not the case. However, the charged liquid surface is an interesting and feasible explanation of the chemical corrosion which cooperates with the mechanical erosion process where relatively low velocity impacts are in question.

<u>Shear</u>

In regard to the sub-surface cracking of glass deHaller[17] says: "One deduces from these facts the inference that it is not so much the normal pressure which produces the disintegration, but rather a tangential stress. This certainly exists: imagine a pressure wave, for simplicity of steep front, penetrating within an elastic body; above the front, the material is compressed and undergoes as a consequence a lateral dilatation which has not yet reached the material below the front of the wave; a shearing stress then appears in the latter. Since the shearing stress is not manifested at the surface of the specimen, the maximum stress is produced in the interior of the body, explaining thus the formation of internal cracks in the glass. At the start of the erosion, the surface previously plane frequently becoming wavy, is deformed before one is able to distinguish cracks or a pulling up of material, as if the underlying layers were destroyed first. This agrees well with the hypothesis.

One can estimate the intensity of the tangential stress; one finds here again that it is of the order of magnitude of the perpendicular pressure, insufficient to explain the rupture according to the usual criterion. It appears that the mathematical theory of elasticity is incapable of furnishing a plausible explanation".

"It is probably necessary to bring into play the molecular structure of the crystal as do the recent theories on plasticity of metals in which they also attribute an essential role to relative gliding of lattice planes".

Dynamic Impact Failure

In their later work with the improved shock wave apparatus Ackeret and deHaller[16] proved that the steepness of the pressure front was determinative. They obtained evidence that an impact type of loading rather than a static loading was required to produce the observed damage. See Part IV, Section 3. Vater[34] concluded from the formation of mechanical twins that impact stress was involved. The X-ray study of Brandenberger and deHaller[8] also showed that water drop erosion may not be wholly a consequence of static stress but may be dynamic in character. If the erosion process is dynamic, the high pressures required to produce static rupture need not be accounted for. The condition for dynamic fracture is only a sufficiently quick load of moderate magnitude. DeHaller[17] says, "It is possible to subject a test specimen to repeated high pressures of the order of 1000 atm and more, without any damage, under the condition that the pressure is not applied rapidly, but increases and decreases progressively, as is the case when the pressure is applied by a piston pump. The same test specimen is not able to resist an effect of 250 atm if this results from an impact. It appears then that it is not so much the absolute value of the pressure which matters, but rather the manner in which it is applied, or more exactly the time which is required for it to attain its maximum, or still the "slope" of the pressure front. An analogous fact has been observed in the study of resilience: the work necessary to rupture a bar diminishes strongly when the speed of the drop hammer increases".

Brandenberger and deHaller[8] have concluded that, "a further clarification of the damage process for drop impact erosion can only be achieved by means of further progress in study of the dynamic break process in which the question of the pressure which actually appears remains of secondary importance".

Spalling

A dynamic process has recently been proposed[43] for the case of protective plastic coatings all of which have a low tensile strength. A pressure wave of steep front moving into the coating from the impact surface is reflected as a pressure wave from the base metal as well as transmitted into the metal. When the reflected portion of the wave returns to the impact surface, it reflects as a tensile wave from the free surface and progresses into the coating until the magnitude of the tensile pull causes rupture. See Figures 7a and 7b. In this way a spall may be thrown out of the surface either as the result of one impact of sufficient magnitude, or as the result of a progressive fracture caused by a number of impacts of lower magnitude. The proposed spalling process is able to explain why thick coatings of any given material are more resistant to erosion attack than thin coatings for which all other conditions including the strength of the bond between the coating and the base metal are identical.

VI. ACKNOWLEDGMENTS

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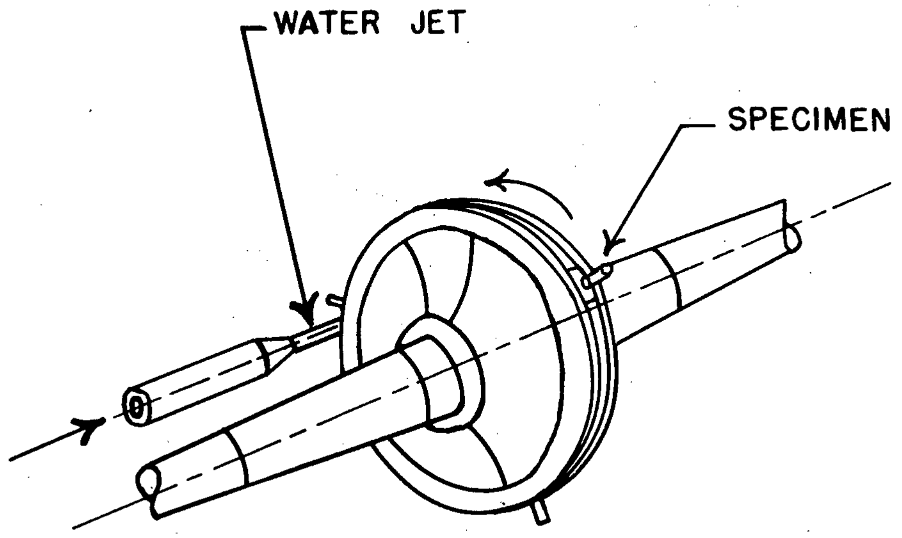
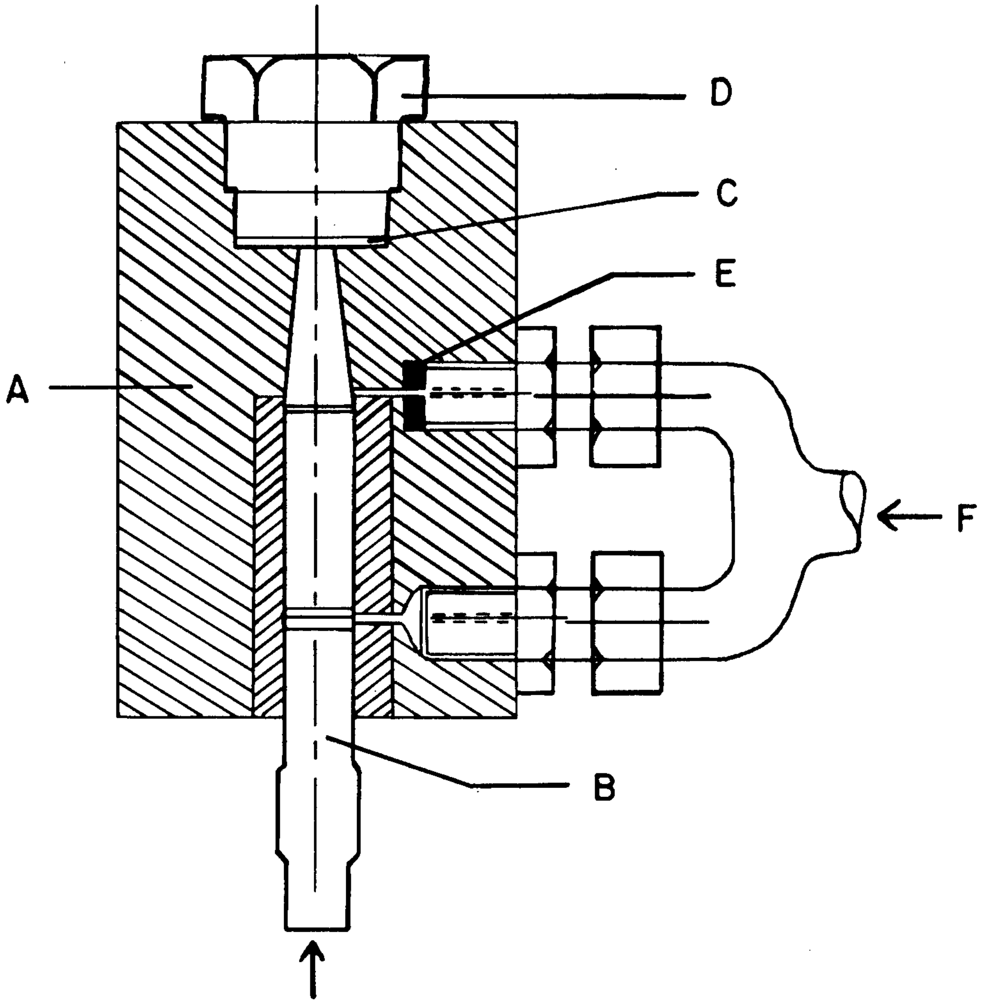


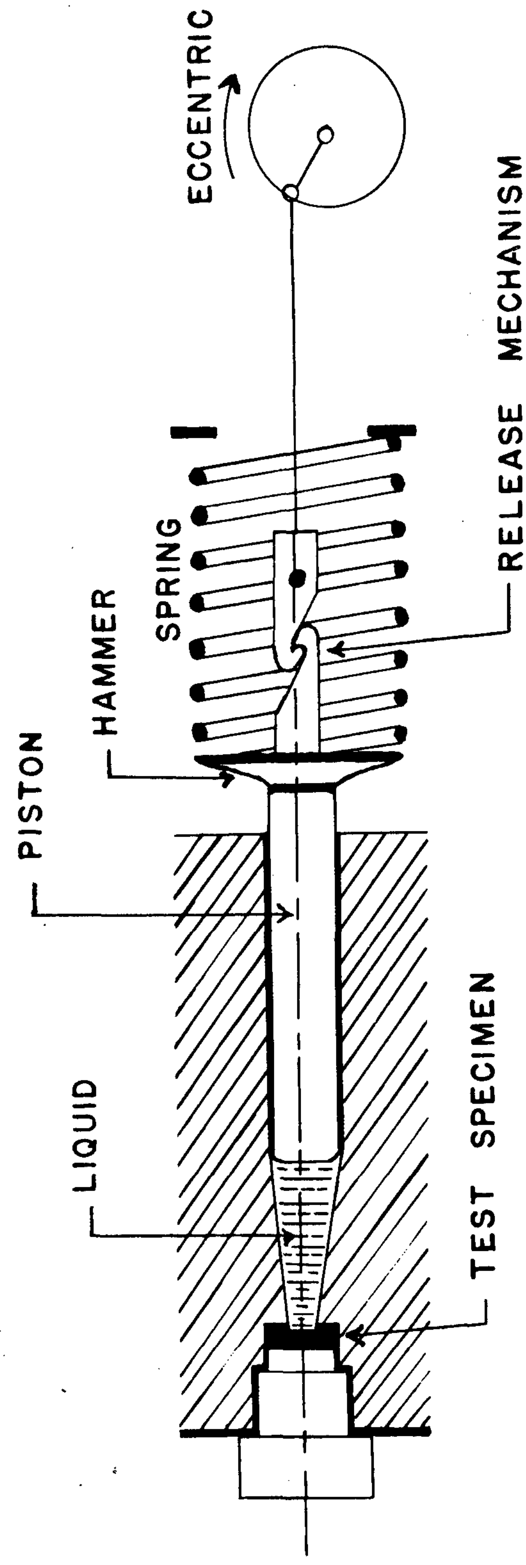
WHEEL AND JET APPARATUS AFTER DE HALLER

FIG. 1



SHOCK WAVE APPARATUS AFTER ACKERET

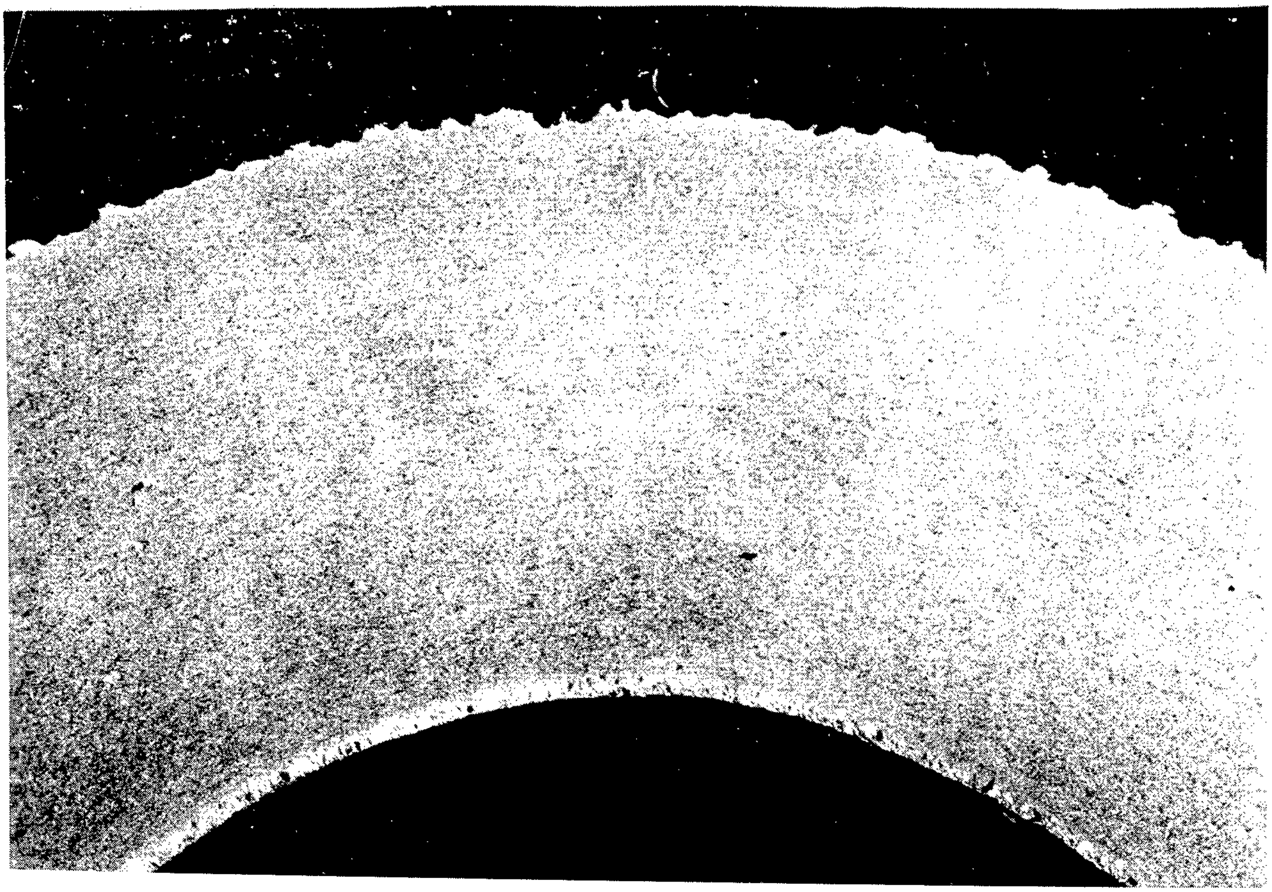
FIG. 2



IMPROVED SHOCK WAVE APPARATUS AFTER DE HALLER

FIG. 3

Figure 4. Erosion of cold rolled steel by a Crystalab Ultrasonorator



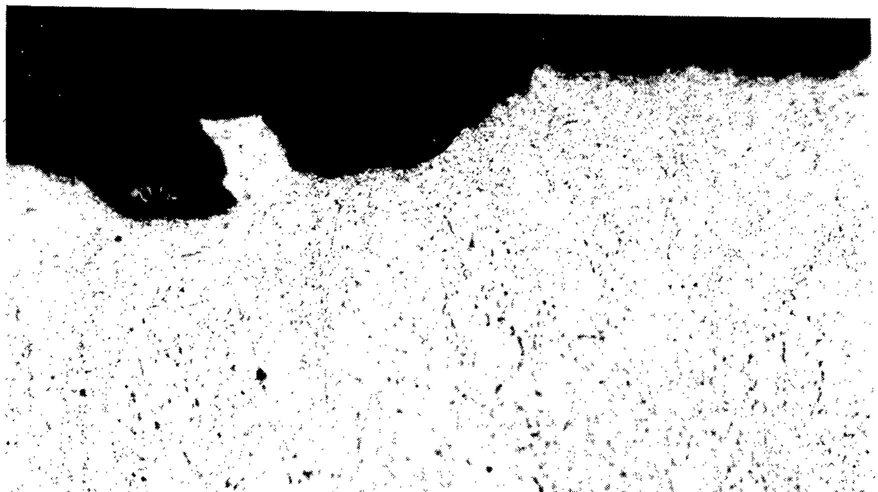
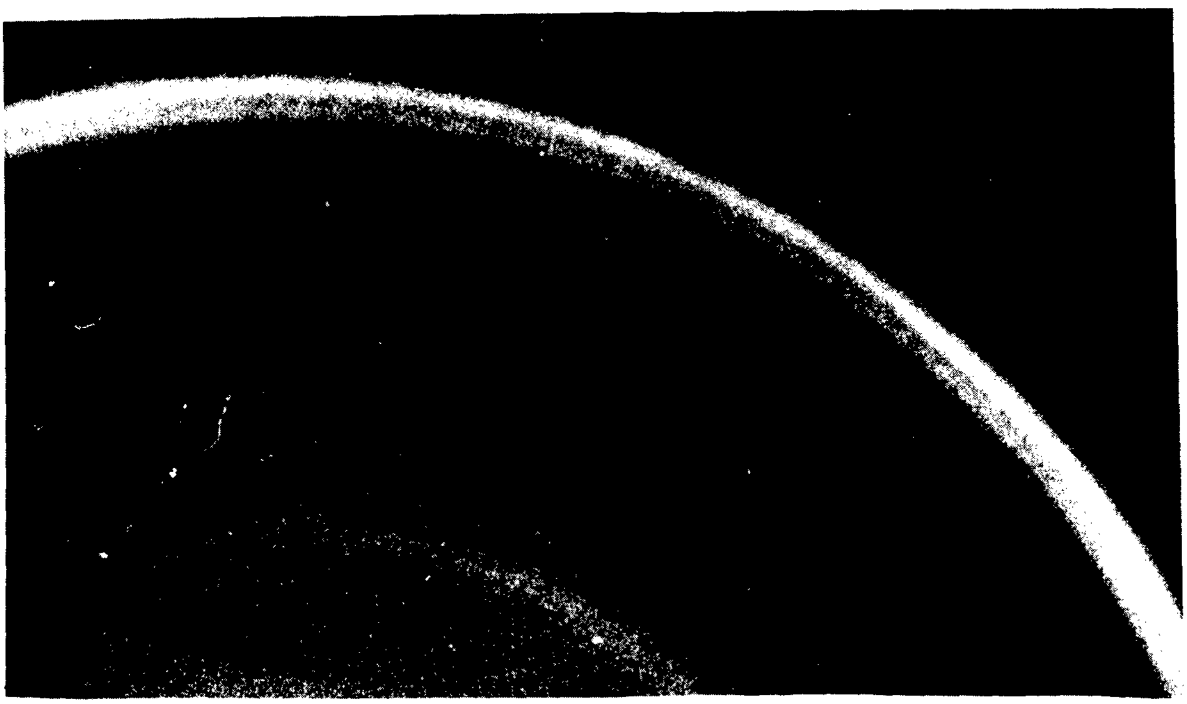


Figure 5. Cross-section of alclad aluminum specimen eroded on the rotating arm tester.

Upper view: Magnification 25X
Lower view: Magnification 500X

Eroded Area



Uneroded Area

Figure 6. The 224 ring of aluminum in an eroded and in an uneroded area.

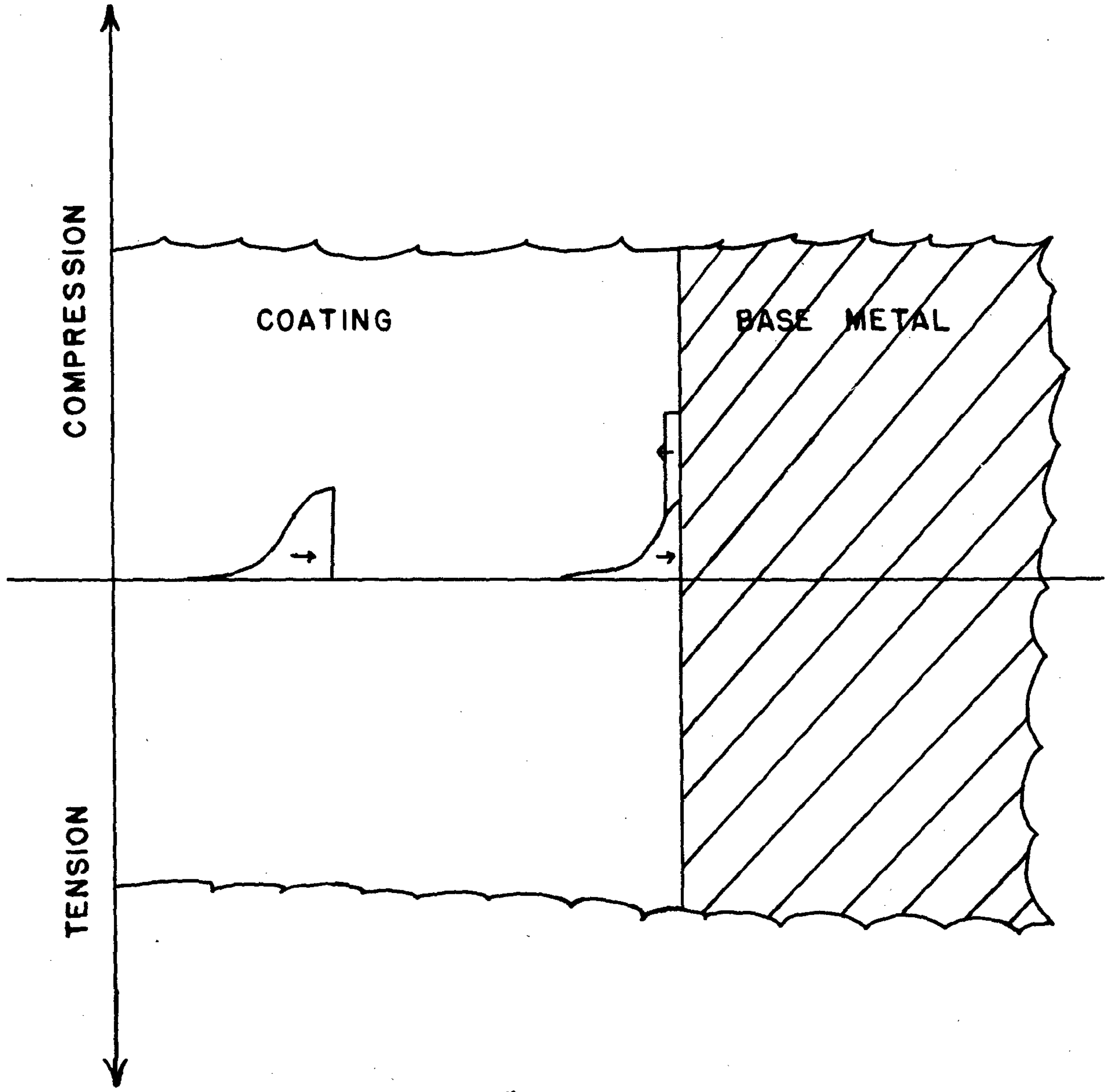


FIG. 7(a)

THE INITIAL COMPRESSION WAVE AND ITS REFLECTION

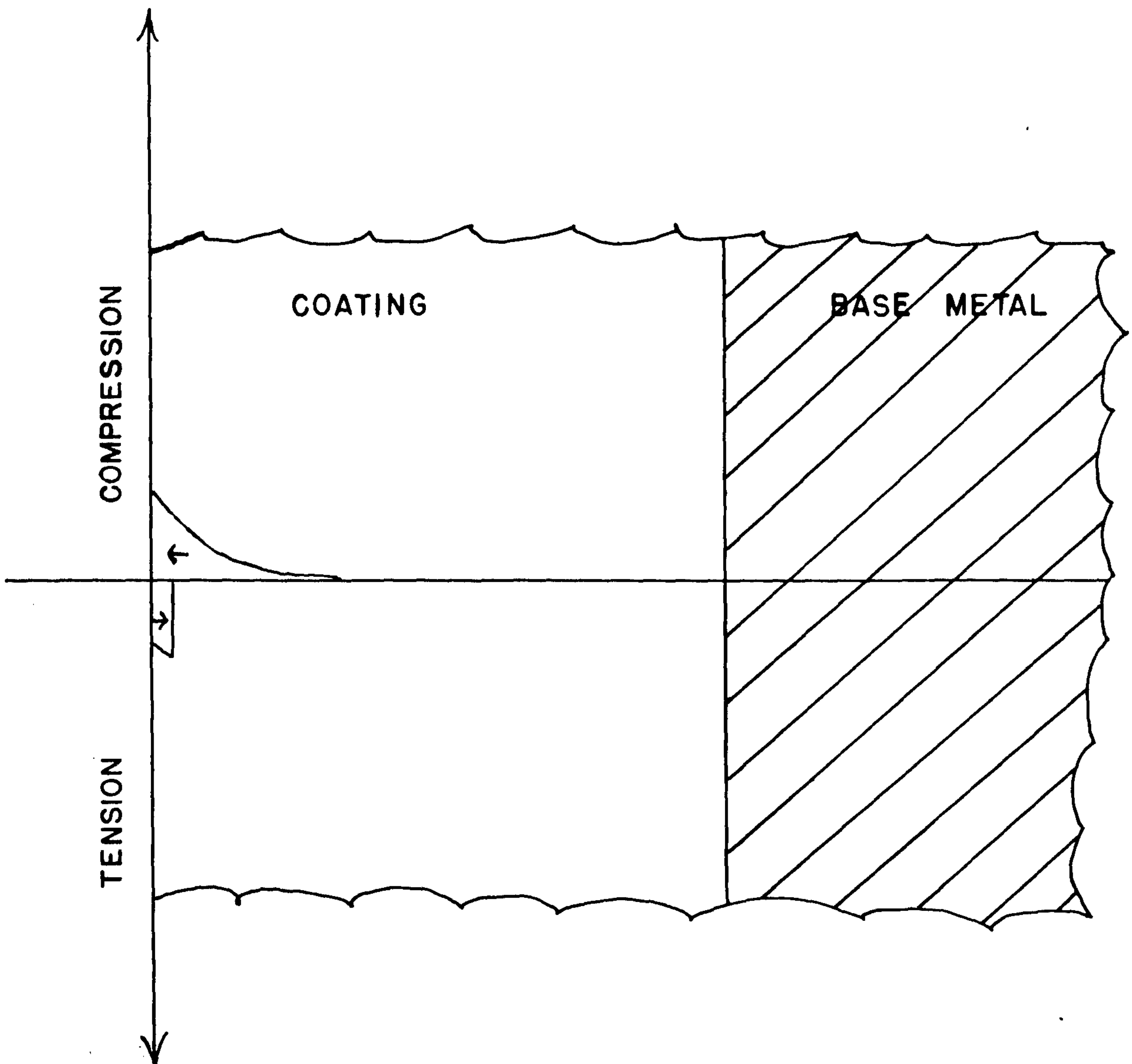


FIG. 7(b)

THE REFLECTION OF THE COMPRESSION WAVE ON ITS RETURN TO THE IMPACT SURFACE